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Design and development of a robotic workstation for the disabled

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DESIGN AND DEVELOPMENT OF A ROBOTIC WORKSTATION FOR THE DISABLED

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SUMMARY

A robotic manipulator system appears to offer much potential for a severely disabled person who has little or no hand function. A robotic system is able to provide a user-controlled manipulative device which is not limited to preselected tasks. This thesis presents the design and development of a robotic workstation at the Bath Institute of Medical Engineering over a period of six years. The design has progressed through three basic systems with potential users involved at all stages.

Initially a survey was carried out of potential users, enabling a picture to be built up of the needs and situations of disabled people. A commercially available robot arm (the Atlas arm from LJ Electronics of Norwich) was purchased to investigate the feasibility of using a relatively low cost manipulator. Five disabled volunteers controlled the robot using a scanning menu user interface system.

On the basis of feedback from the feasibility study the Atlas arm was integrated into a workstation, with various tasks arranged radially around the arm. This system underwent trials with six high level tetraplegic volunteers. From this

experience the specification for a new arm was defined.

A new manipulator was designed and constructed, of a jointed cylindrical configuration mounted within a compact desk. This workstation has been tested both in a hospital environment and in the homes of disabled people.

This work has proved the feasibility of the control of a robot manipulator by a severely disabled person. Various potentially useful tasks have been carried out by the robot. A robotic workstation can provide a useful aid in an appropriate situation.

ACKNOWLEDGEMENTS

A project of this size is by nature the work of a team rather than any individual, and numerous colleagues at the Bath Institute of Medical Engineering (BIME) have been involved at different stages of the work. Early in the project the user survey was carried out by Tyrone Clay, an ergonomics student on placement from Loughborough University. The electronics control for the Atlas system was designed by Andrew Gammie.

In the design of the Wolfson workstation a greater number of people have been involved. The mechanical design (with the exception of the gripper) was carried out by Graham Pullin, a research officer at the University of Bath in the School of Mechanical Engineering. The electronics hardware design was again carried out by Andrew Gammie. The construction of the system was carried out by Martin Rouse and Peter Laidler mechanical and electronics technicians repectively. In the later stage of the project Jill Jepson, employed by BIME as an occupational therapist, has been involved in the user trials and evaluations. Throughout the project Roger Orpwood has carried the responsibility of project management and we are grateful for his guidance and advice.

Graham Pullin has a great interest in aesthetics and industrial design and I am grateful to him for introducing this as a major aspect of our work. On a similar note I am grateful to him for permission to use his sketches in Chapter 14.

A major part of the work has been evaluation of the systems with potential users. I am therefore grateful to the occupational therapy staff and patients at Odstock hospital for their part in the project and to all the other volunteers who have used and commented upon the various systems.

BIME relies for much of its funding on the generous support of regular donors. The robot project has also benefitted from specific financial assistance. I am grateful to the Department of Health and Social Security (as it was then) for funding my study trip to the United States. The Wolfson Foundation have been most generous in the grant which they awarded us to design our own manipulator. Another generous grant awarded by the Wessex Regional Research Committee has funded the evaluation and ongoing development of the Wolfson workstation system.

Rehabilitation Robotics is a very rewarding field to be able to work in. I have benefitted greatly from the opportunities at conferences and workshops, to meet and share ideas with workers from around the world involved in similar projects. In particular I would like to thank the team at Cambridge University Engineering Department, Robin Jackson, William Harwin and Ray Gosine, for their encouragement and friendship.

Finally my thanks to my wife Jan for her support and encouragement and patience when I have disappeared to the wordprocessor.

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Chapter 1. INTRODUCTION

INTRODUCTION

For the severely physically disabled person, particularly those with limited or no hand movement, the ability to control their environment is very important if they are to retain any independence. For some this independence might mean living in their homes relatively unaided, although in most cases it will be a matter of not being so totally dependent on others for every aspect of life.

Environmental control systems (ECS), such as the Possum system, fulfil an important role, but can only be used with preselected pieces of equipment which are electrically operated. To overcome these inherent limitations, the use of a robotic manipulator has been proposed. This might be used either as an extension to a computer controlled ECS, or as an independent device.

There are three main types of robot which have been used in rehabilitation applications. Probably the most widely used is a fixed site manipulator arm. The fixed site may be on a desk or tabletop or suspended from a ceiling mounted track. In all such applications the working envelope of the robot is restricted. To increase the area of operation of the robot it must be made mobile. This may be achieved by mounting a manipulator on a wheelchair. Alternatively the robot may be made freely mobile, either autonomously or under remote control. Freely mobile robots which do not include a manipulator have been suggested for patient mobility and other applications.

In a review of worldwide rehabilitation robotics research [1], produced in 1989, Prior identifies 56 projects worldwide. Of these 28 are in the USA, 8 in Canada, 18 in Europe and only 2 in Japan. 29 of these projects are workstation based, 4 are wheelchair mounted, 10 are mobile and 13 come into other categories. 15 projects use purpose built manipulators and of the other projects 11 use the UMI RTX (Middlesborough, UK) arm. These figures do not include other healthcare applications, such as robotic lifting devices to replace some of the functions of nurses and porters, robots to aid in surgical operations and robotic prostheses.

Information from a study of the published literature is augmented by information gathered from attendance at conferences and during a visit by the author to the United States in 1987. This visit was funded by the Department of Health and Social Security.

EARLY WORK

The first recorded rehabilitation manipulator was the CASE manipulator [2], built in the early 1960's. This was a powered orthosis with four degrees of freedom, which could move the user's paralysed arm. Another early powered orthosis was the Rancho Los Amigos manipulator [2] with seven degrees of freedom. Other pioneering work, with relevance to rehabilitation robotics, was in the area of powered upper arm prostheses.

Early work in the more specific area of rehabilitation robotics started in the mid 1970's. One of the earliest projects was the workstation based system designed by Roesler [3] in West Germany. The purpose designed, five degree of freedom manipulator was placed in a specially adapted desktop environment, using rotating shelf units. The user input was a mouth operated joystick.

Another early workstation system was that of Seamone and Schmeisser at the Johns Hopkins University, supported by the Veterans Administration in the United States from 1974 [4]. The arm of this system was based around an electrically powered prosthetic arm, mounted on a horizontal track (Fig. 1.1). Various items of equipment (eg telephone, book rest, computer discs) were laid out on the simple but cleverly designed workstation table and could be manipulated by the arm using preprogrammed commands. The system thus required that items be in precisely known positions as there were no sensors on the arm. The system could also be used for feeding, using a specially designed spoon. User input was by simple scanning switch selection of routines on a simple LED display. The system was selected by the Veterans Administration for small scale manufacture and trials, though difficulties arose in arranging the manufacture of the non-standard arm.

In France, an early project was the Spartacus robot [5], based around a large high quality manipulator from the nuclear industry. The table mounted arm was able to reach down to the floor or up to a shelf. Fairly complex movements of the arm were controlled by disabled users through a number of analogue input devices, particularly a head position operated joystick. With such a potentially powerful device, safety had to carefully considered and early training of users was done with the arm behind a clear screen. This project has led to the Manus project in Holland and the Master project in France, described below.

The earliest project in the United Kingdom was by Todd at Queen Mary College in 1977 [6]. This was a feasibility study into the control of a simple manipulator via a microcomputer. Various input devices were used to drive the robot both by direct control and by preprogrammed actions. The study was funded for only one year, and was not continued after the initial feasibility phase, though the results were not unfavourable.

Another early project in the United States was the work of

Mason [7] at the Veterans Administration Prosthetics Center in New York. This was the first use of a robot arm mounted to a wheelchair, potentially offering much greater freedom than a workstation mounted system. The four degree of freedom arm was beautifully engineered, and its novel telescoping design allowed it to reach to the floor or the ceiling. However its range led to its main failing of being far too springy and having insufficient force. Control was initially by joystick, but at a later date developed to voice control. There was no feedback from the simple prosthetic hook gripper, instead relying on the user's vision of the arm.

FIXED SITE ROBOTICS

Commercially available manipulators

One of the major projects is that led by Leifer at Stanford University, California, with the Palo Alto VA Hospital. The approach has been to use a high cost, high specification industrial manipulator. Since the project started in 1980 four generations of DeVAR (Desktop Vocational Assistive Robot) have been developed. The third and fourth generation workstations share the same hardware, but are aimed at different environments. The manipulator used is a Puma 260 industrial robot fitted with an Otto-Bock Greifer prosthetic hand gripper. The control software is implemented on an IBM PC microcomputer, with user input through a VOTAN voice recognition system.

The DeVAR III workstation [8] is set up for daily living tasks, including feeding, shaving and brushing teeth. The robot is mounted near the centre of a 3' by 6' table and is surrounded by a refrigerator, microwave and a small equipment holder. The control computer is mounted on a separate trolley, positioned where the user can see the colour monitor. The DeVAR IV workstation [9] (Fig. 1.2) is aimed at a vocational environment, and the prototype is set up in the office of a disabled programmer. The Puma arm is mounted upside-down on an overhead track, thus increasing its working envelope. The system is used for tasks associated with computer use, telephone operation, handling of manuals and other paperwork and personal tasks. The vocational system is being commercially marketed at a cost between $50,000 and $100,000. This includes the cost of the high specification arm and the installation and setting up in a vocational environment.

Other projects based around commercially available robot manipulators have chosen devices with a lower specification and hence lower cost. Many of these cheaper manipulators are sold primarily to the educational market.

The Cerebral Palsy Research Foundation of Kansas has developed a light industrial application of a low cost robot [10]. A Microbot manipulator and a home computer are used to perform the tinning of electronic components prior to soldering. The arm moves through a preprogrammed motion, and the disabled operator is only in the control loop to give quality inspection and indexing of the parts. Besides the Microbot a Feedback Armatrol has also been used. Both of these arms sell for less than $4000 and though useful were found to be unable to cope with the rigours of continuous operation. Subsequently an industrially rated Microbot has been purchased at a cost of $14,000.

At the Kaiser Rehabilitation Centre at Tulsa, Oklahoma a simple inexpensive bedside "care unit" is being developed [11]. Operated by voice or a suck/puff input the manipulator will provide drinks etc to the user. The manipulator used is produced by Micro-Mega and is a cheap five degree of freedom device.

Often the use of a commercially available robot may be just the first stage to prove the feasibility of a project. At the University of Saskatchewan [12] a small industrial arm, though not ideal, has been incorporated into a vocational workstation for typical office tasks, to demonstrate the concepts involved. At Carnegie Mellon University a CRS M1A robot [13] is being used, mounted on a horizontal track, for a vocational application. They appear to see the commercial robot as a first step towards designing their own manipulator.

The workstation projects described so far have used either a high cost industrial robot, or a low cost educational robot. One robot which is widely used however sits between these two categories, and has been actively promoted by the manufacturers as being suitable for rehabilitation applications. This is the RTX and similar but higher specification RT100 produced by the UMI Group (Middlesborough, UK). The arm is illustrated in Fig. 1.3. The arm is a six degree of freedom modified SCARA (jointed cylindrical) arm with the vertical actuator located in a large vertical post. All the joints are DC servo motor driven.

An early system based around the RTX was developed at Boeing in Seattle initially for one of their own disabled programmers [14]. The system is aimed at the vocational programmer. A UMI RTX robot is controlled by voice to insert computer discs and get computer manuals. The IBM computer used by the programmer is also accessed by voice command. The system has been marketed in the United States by PRAB Command Inc., the importer of the RTX robot.

In France the Master project [15], a continuation of the Spartacus work, uses an RTX robot in a workstation environment. The manipulator is mounted at the back of the workstation, with shelving units on both sides which may be accessed by the arm. The system includes an environmental control facility. The standard RTX gripper has been replaced by modified interchangeable gripper units with force sensing. The use of switch and analogue inputs allows the disabled user to control the arm by a combination of direct and automatic control modes.

Due to the wide use and proven applicability of the RTX several groups are concentrating on particular aspects of its use and application. It is therefore important that the accumulated expertise with the RTX is combined rather than reinvented. At the Tufts Medical Centre in Boston a UMI RTX robot is being used to provide a vocational robotic workstation. Particular emphases of the work have been the CALVIN robot language [16], voice control [17] and automated gripping [18]. At the Hugh MacMillan Medical Centre in Toronto [19] the RTX is being used in a general purpose robotic aid. Particular emphasis is on automated grasping under the direct voice control of the user.

A number of RTX and RT100 units have already been installed in vocational settings and are in practical use. One unit is installed at HADAR (Malmo, Sweden) for paper handling in a clerical situation. Another unit is at the Karnsjukhusset/Handikapp Institutet, also in Sweden.

Purpose designed manipulators.

Normally the most efficient and cheapest way to produce a robotic system is to use a commercially available device. There may however be good reasons for designing a manipulator for a specific situation. Valid reasons include more succesful integration of the overall system, designing to a known specification for more effective operation, a possibly cheaper system if the specification is simple and finally avoiding reliance on a particular device supplier.

At the Neil Squire Foundation in Vancouver, Canada [20], a workstation robot has been developed (Fig. 1.4), based around a six degree of freedom manipulator mounted on a horizontal bar, thus allowing sideways movement over a bed or table. The manipulator is able to rotate through nearly 360 degrees around the bar, with extension and translation along the bar. User control is through specially written software on an IBM PC microcomputer. Various input methods may be used including voice, switch scanning and coded input. Their aim is to produce an affordable device, firmly grounded on the needs of the disabled. Several systems have already been sold, and it is being actively marketted.

The Georgia Institute of Technology, Centre for Rehabilitation Technology, has for several years been developing an "ABLE

Office" environment, incorporating adjustable carousels etc., to assist a disabled person working in an office. A robot manipulator is envisaged as part of this system, and a prototype has been installed. Experience with this first manipulator has led to the defining of a specification for a new arm, with the priorities of reliability, dexterity and affordability. The manipulator [21], still under development, has six degrees of freedom. Each of three joints incorporates pitch and roll through an inverse differential gear arrangement. Each motor has both an analogue and a digital control board incorporating a 68000 microprocessor. The digital boards are connected to a main control unit, communicating to a host computer. In order to keep the price below a target of $10,000, the arm is also intended to sell to the industrial robot market, thus increasing the market size.

Powered Feeding devices.

Besides general vocational and daily living tasks, fixed site robots may also be valuably used for more specific and limited applications. One such application is as a robotic feeder. Since a much less critical performance is required from the arm it is possible to reduce the price significantly. Davies and Semple developed a feeder in Adelaide [22] for an estimated cost of a few hundred pounds. The simple stepper motor driven manipulator was controlled by children with cerebral palsy using a simple keyboard. Besides feeding it was able to draw and turn pages, though it is assumed that such ability was crude.

At Keele University a robot aid to eating [23] (Fig. 1.5) has been developed, based around a Cyber Robotics educational robot. The project team have concentrated on developing solely the feeding application and claim impressive results. Approximately 40 "Handy 1" units have been delivered and are in regular use across a wide age range. In some cases the use of the feeder has improved posture and mouth control to an extent that the user no longer needs the robot. User control is very simple, using a scanning system of lights mounted above the plate to choose from different items of food. The five degrees of freedom of the Cyber robot are probably not necessary for the required motions.

Another feeding device, which uses a purpose built mechanism has been built at the University of Delaware [24]. The mechanism has only three degrees of freedom for spoon extension, spoon rotation to dip into bowl and bowl rotation to select food.

Robots in education

Several projects have been aimed specifically at disabled children. Cambridge University [25] have used the UMI RTX as an educational aid for children with cerebral palsy (Fig. 1.6). For such children the ability to "play" is missing. Therefore the robot has been used to simply drop a brick onto a drum, producing an interesting noise. This has then progressed to exercises such as colour matching where different coloured bricks are held over various colour coded receptacles. When the colours match, the child gives the signal to drop the brick into the receptacle. Applications are developed depending on the needs of the children, and on comments from both children and staff. The robot has been used at a more advanced level to enable the children to take part in cookery and chemistry lessons.

Much of the developmental delay of physically disabled children, such as those with cerebral palsy, occurs at a very early age when they are not able to interact with their environment. Researchers at California State University [26] have introduced a robot to children three years and under. A cheap robot is programmed by the therapist or teacher through a series of movements which will be of interest to the child, for example picking up a biscuit and moving it nearer to the child. The child controls the robot by pressing on a single switch which, while it is depressed, allows the robot to move through the preprogrammed movements.

A similar project at Purdue University, Indiana [27] has used a robot with physically disabled children aged 2 to 9. The robot is controlled by a multi-switch unit with pictures of different toys. When a switch is pressed the robot will pick up and bring to the child the appropriate toy from the toy rack.

The Ohio State University have been involved in the design, development and testing of robotically aided educational environments for physically disabled students since 1986 [28,29]. The specific focus has been on the use of robotics in the science laboratory. The robotically aided system must be integrated into the science education environment. The student must learn to use the robot system competently and then to participate in the academic experiences. The robot used is the UMI RTX controlled by an IBM PC microcomputer with a simple switch input. The user interface software aims to be easily understood, while incorporating a number of powerful functions.

Therapeutic applications

Whilst the majority of rehabilitation robotics projects have focussed on using robots as assistive devices, a smaller number of projects have used robots as therapy aids. For muscle re-education after a stroke a therapist will move the affected extremity through various therapeutic patterns. As the patient moves his limb more independently, he will be directed by the therapist to touch different points in space. This latter function has been replaced by the use of a UMI RTX robot at the Rehabilitation Institute of Michigan [30]. The robot holds a touch pad and the user is instructed alternately to touch this pad, and a fixed home pad. The benefits are a possible cost saving in therapists' time, but more significantly improved therapy through precise positioning and objective monitoring of a patient's performance.

At Santa Clara University two planar robot arms have been used for the rehabilitation of joints and for the estimation of body segment parameters [31]. The two arms, each with force sensors at base and gripper, hold firmly two adjacent limb segments (eg upper and lower leg). Continuous passive motion is a technique used after surgery for joint rehabilitation. Using the two robots, the leg is manipulated, with the joint under compression for effective rehabilitation. Mathematical analysis of the same robot system can determine values of the body segment parameters. Knowledge of these parameters is important for the design of prosthetic and orthotic devices.

Another application (California State University [32]) is to use a myoelectrically controlled robotic arm for the biofeedback training of people with cerebral palsy. It has been noticed that the muscle activity patterns of people with cerebral palsy are different from those of able bodied persons. Thus, it is postulated that the performance of a muscle task may be improved by the use of biofeedback. In this application electromyograph (EMG) signals from the biceps and triceps are used to control a small robot arm, providing the subjects with an additional visual feedback of muscle performance.

WHEELCHAIR MOUNTED ROBOTS

Although the use of robotics is intended to bring flexibility, the workstation approach is itself limited. A fixed site robot arm can only interact with objects arranged (by an able bodied person) around it. However in daily living the objects to be manipulated may include a book on a book shelf, preparing a meal in the kitchen and operating a word processor in the study. The idea of a mobile robot is therefore very attractive. Two approaches may be considered, an autonomous mobile robot freely roaming about the house or a manipulator mounted to an electric wheelchair which moves with the user.

A wheelchair mounted robot developed in the Netherlands by a private individual (Zeelenberg [33]), for his son who has muscular dystrophy, has been particularly successful. The arm is a cheap educational robot, sitting on the lap board of a wheelchair and the use of an external microprocessor has been avoided. Many useful tasks have been accomplished, including page turning, feeding, ringing a door bell, opening a door and playing chess. The success of this project is due to a number of factors, including a motivated user receiving individual attention. The remaining control abilities of someone suffering from muscular dystrophy have allowed the use of a multi-switch input.

Recent work in the mounting of a manipulator to a wheelchair has been carried out at the Hoensbroek Institute for Rehabilitation Research (Netherlands) by Kwee [34], who previously worked on the Spartacus project. The Manus project aims to produce a moderately priced wheelchair mounted manipulator. The manipulator is an articulated arm on a telescoping base (Fig. 1.7). In order to keep the mass and inertia of the arm low, drive is by DC servo motors mounted in the column via belts, gears and concentric hollow shafts. The construction of the arm includes aluminium castings and carbon fibre tubes. When not in use the arm will fold away at the side of the chair. The manipulator may be fitted to a number of different electric wheelchairs. Computer control is through an onboard microprocessor system in an IBM PC environment. The system may be set up for individual users by a therapist via an external microcomputer.

Another wheelchair mounted manipulator is being developed independently by Jim Hennequin and his Inventaid company [35]. This manipulator is based around a novel pneumatic actuator, known as an "Air Muscle" [36]. Air is fed into a coiled bag, the expansion of which causes the joint to open. The actuators are very compact, yet powerful, leading to a slim, light weight manipulator. Simplicity (with implications for low cost, reliability and easy maintenance) has always been one of the aims of the project and the basic system involves no digital or microprocessor circuitry. The arm is therefore moved by control of the individual joints rather than in cartesian space.

MOBILE ROBOTS

One of the earliest projects attempting to use a mobile robot in a rehabilitation setting is the MoVAR (Mobile Vocational Assistive Robot) project (Fig. 1.8) at Stanford University [37]. This has been carried out in parallel with their development of the DeVAR desk top robot. A small Puma industrial arm is mounted on an omnidirectional mobile platform. The platform has a novel wheel arrangement allowing it to travel in any direction, though it is limited to a single floor of a building. Control of the platform is either by the use of direct voice commands, or by the planning of the platform trajectory in advance on a floor plan displayed on a computer screen. The arm carries a video camera which allows the user to control the arm in another room. Control of the arm is through the use of voice control. The user sits at a console and has three screens (including the video display) to aid in controlling the robot and platform. Ultimately however it is intended to control a mobile robot using an English language interface.

At Rice University [38] a Hero 2000 robot, modified to extend its workspace to cover from floor to desktop height, is being used for rehabilitation applications. It is able to move about a structured indoor setting in a semiautonomous fashion and uses teleoperator control mode for simple pick and place operations. It is also able to control domestic appliances. Control of the system is through the use of a graphical interface on a Macintosh computer.

At Dundee University [39] the feasibility of using a low cost, unsophisticated mobile robot has been evaluated. The system tested consisted of a mobile platform with a variable height gripper. Control was by a radio link from a hand held controller. The system was tested with disabled people, and the results indicated that even such an unsophisticated robot could offer scope for increased independence for the disabled in their domestic setting.

Engelberger [40] describes the HelpMate robot, being developed by the Transitions Research Corporation (Danbury, Connecticut). Although aimed primarily at a hospital environment to bring food trays etc. to a patient in bed, the application as a fetch and carry robot for the disabled is obvious. The HelpMate is multi-sensory, using a combination of dead-reckoning and various sensor systems for navigation and collision avoidance. A map of the location is embedded in its onboard memory. Multiple sensors are used for manipulation purposes.

A project which is proposed in the UK [41], involving a number of research establishments and with the support of the DTI under their Advanced Robotics Initiative, is to develop a mobile robot which will dock with various workstations. This use of a semistructured environment will allow the use of preprogrammed routines, thus reducing the control burden on the user.

At the University of Michigan it is proposed to use a mobile robot as a task guidance system for a person with cognitive impairment. As an example a person may suffer from spatial disorientation and memory deficiency. For a simple job such as cleaning rooms in a hotel a mobile robot could be used to guide a person to the rooms of the building and through the essentials of the task. The technology involved includes the ability to follow or lead the person, obstacle avoidance and task planning. The obstacle avoidance has been tested on a commercially available Cybermation K2A base [42] and this system is now being transferred to a Denning mobile base to implement the rehabilitation application [43].

A mobile robot is also being used to guide a person with sensory impairment [44]. The robot is essentially a robot guide dog for the blind, known as "Meldog", and is able to lead a blind person around a known environment. Information on the area is input to the robot's memory from an off-line computer scanning an ordinary street map. At each street intersection the robot's actual position and orientation is updated by reference to known landmarks. The presence and identification of these landmarks must therefore be previously input to the robot. As well as navigation, the robot also has onboard optical and ultrasonic sensors for obstacle avoidance.

Powered Mobility

An extension of the use of mobile robots for manipulation is to provide mobility for disabled people. Various sensor and guidance systems may be used to decrease the control burden for the person using a wheelchair, though in most cases the user will want to retain overall control. An intelligent input system may also be beneficial, for example for those with extreme tremor. A survey carried out at the Hugh MacMillan Medical Centre, Toronto [45] has investigated what "smart" features are most needed by persons with particular disabilities. The groups considered were the physically disabled, the developmentally delayed, the blind and the elderly. Of the features most relevant to a discussion of robotics, obstacle avoidance was widely specified as were door entering and table docking functions. For the developmentally delayed the ability to follow a person or line following was specified. All functions should be easy to use.

At the Chailey Heritage Hospital in the UK an introduction to mobility for a very young disabled child uses a mobile platform and a track following system [46]. The child's special seating system may be fitted to the mobile base. Control by the child is initially simple stop start commands from a chin switch. At a later stage this may extend to choosing a direction at a junction in the track. The track is simply a wire located underneath a carpet, or taped to the floor in the school.

The VAHM (Autonomous Vehicle for the disabled) project in France [47] aims to mount a robotic manipulator on a powered wheelchair with features for autonomous movement. The intelligent mobility will include localisation of the wheelchair within the environment, path planning and local features such as obstacle avoidance and wall following.

At the National Research Council of Canada [48] an intelligent platform for healthcare applications is being developed. Three possible applications have been discussed, an autonomous wheelchair, an "auto porter" which would push a standard wheelchair, and an autonomous walker. It is envisaged that such devices might enable the disabled or elderly to live at home or in small group homes. Work has focussed on the development of an autonomous platform to transport residents around an institution for the elderly.

At the CALL centre in Edinburgh [49] a smart wheelchair for children and teenagers has been built, based around a standard Everest & Jennings Electric Wheelchair. The system uses a modular "toolkit" approach so that features may be added or omitted as necessary. Amongst the functions developed are bump sensors, forward looking ultrasonic sensors, infra-red line following and various user input options. The chair has been used successfully with four users aged between 10 and 17 years.

EVALUATION

While the bulk of the published work on rehabilitation robotics has centred on the engineering aspects, an increasing number of papers are appearing presenting the results of clinical evaluations. The Johns Hopkins University workstation system [50] has been evaluated with 20 male patients with spinal cord injuries, aged between 21 and 60 years, in their homes and at 2 different clinical sites. One subject used the system for 100 hours total. The main uses of the system were eating meals (a total of 316 meals eaten) and answering the telephone. The general response was of a potentially useful system, but with deficiencies particularly of the speed of operation and the user control aspects. One particular problem encountered was the difficulty encountered by those subjects who needed to be reclined in their wheelchairs.

Another workstation system which has been extensively evaluated is the DeVAR system from Stanford University. The DeVAR III system [51] is aimed at daily living tasks. 24 high level tetraplegics used the system to carry out a number of preprogrammed tasks, preparing and feeding soup, shaving, using a toothbrush and washing the face. A large majority were satisfied with the system and felt that it increased their independence. The DeVAR IV system has been installed in the office of a disabled programmer, and has been in continuous use for 18 months, carrying out vocational and daily living tasks [52]. It was determined that the robot would be an effective replacement for an attendant if it could allow the disabled employee to work totally independently for a minimum 4 hour continuous period per day. On this basis the robot system could pay for itself in two years. In practice two five hour shifts per day have proved feasible, with the attendant only necessary for setting up in the morning, lunch hour and evening.

The use of an inexpensive educational manipulator mounted on the lap board of a wheelchair has been evaluated for 6 patients with muscular dystrophy [53]. For those with this disease a finger activated control input may be used making direct control relatively easy though programmability is a valuable extra feature. The robots were used for feeding, manipulation of environmental control equipment and recreational activities. Control and movement of the essentially unmodified robots in joint mode was slow. It took over an hour to eat a meal, though this was comparable with the time taken for attendant feeding due to the weakness of masticatory muscles. The results indicate the potential of direct control of a wheelchair mounted manipulator for those able to use a finger activated control input.

The Handy 1 eating aid from Keele University is in use with 36 people, aged from 4 to 82 years. A survey of 20 users of these aids was carried out [54], interviewing the user wherever possible, though in the majority of cases his or her carer. Those interviewed had used the aid for betwenn 3 and 30 months, for at least one meal a day. Many positive aspects of the aid were mentioned. Though rarely saving time for the carer, who needed to be on hand, there was a much more relaxed, sociable atmosphere. Use of the aid often identified problems of poor seating (which were corrected) and improved head and mouth control.

Assessment of those who will use a robotic aid avoids wasted research effort and misplaced equipment. Amongst the placements of the Handy 1 robot there were a small number of failures which were related to the correct assessment procedure not being followed. Hammel [55] at Palo Alto VA provides a model for assessment. Initially the user should be assessed for his cognitive status, physical function, medical status and needs. Following this the individual is observed for two days in his home/work environment, generating a graph of a typical day. Following these evaluations the workstation can be adapted to fit the individual needs of the user.

Evaluation of the reaction of healthcare professionals is also important to determine the acceptability of rehabilitation robotics. Occupational Therapists working with the Stanford University robotics project specifically aimed a questionnaire at other OTs [56] working in the San Francisco area. The results show a general interest among OTs in robotics and the view that robots would be useful in a vocational environment. There was a strong feeling that OTs should be the the professionals responsible for training patients to use a robot. When questioned on cost between $1000 and $5000 was considered acceptable.

JUSTIFICATION OF BIME APPROACH.

As noted above, over 50 projects have been identified, involved in the application of robotics to the needs of the disabled. To date very few of these systems have become a commercially available product, and many have not progressed past the prototype stage. It is therefore necessary to justify the involvement of the Bath Institute of Medical Engineering in rehabilitation robotics.

The Institute is a charitably funded design and development organisation in the field of medical engineering. About 70% of the projects undertaken by the Institute concern aids for the disabled and rehabilitation equipment and the remaining work concerns items of hospital equipment. The Institute is part of the University of Bath, and has close working relationships with research staff of the University and with hospitals both in the Bath District and elsewhere in the country. The Institute is located in the Wolfson Centre in the grounds of the Royal United Hospital, Bath. Particular links which are of importance in the robot project are with the Duke of Cornwall Spinal Injuries Unit at Odstock Hospital, Salisbury, with Dr A.K. Clarke, Rehabilitation Consultant at the Royal National Hospital for Rheumatic Diseases, Bath, and good contact with the Department of Health. The Institute therefore brings these contacts, and many years of working with and for the disabled community to the robot project.

One of the main aims of the Institute is to develop devices to the stage where they can be made commercially available, either through licensing the design to a manufacturing company, or through in-house production. This has been born in mind in the robot project, and from the early stages of the project Hugh Steeper Limited (manufacturers of prosthetic limbs and environmental control systems) have shown an interest in our progress.

With a commercial market very much in mind, the cost of the final product has been an important factor. An approximate price target of £6000 has been set, based on the type of money which it is felt the Department of Health might be willing to prescribe. This cost is being aimed at by using existing technology which is easily available, rather than the more advanced robotic technologies which are only just emerging.

Though wheelchair mounted manipulators and freely mobile robots show great potential it was felt that results could be obtained quicker by initially aiming the investigation at a workstation robotic system.

EVOLUTIONARY DESIGN

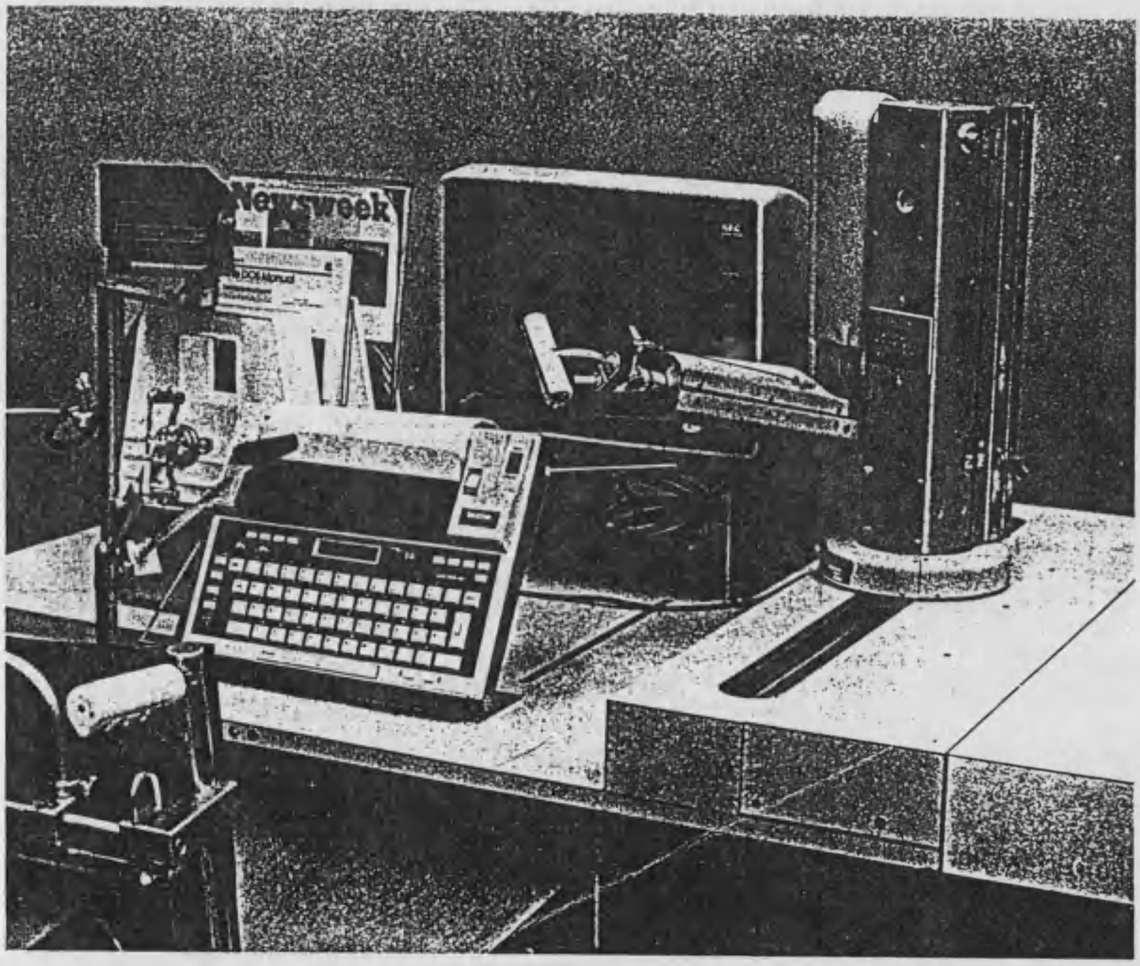
Experience with potential users is vital at all stages in the design of rehabilitation robotics. For equipment which has to operate intimately with a human user it is not possible to write a simple engineering specification. Rather there must be an iterative loop of constructing a basic prototype and refining it (and the specification) through tests with users [57]. This thesis presents the design of a robotic workstation at the Bath Institute of Medical Engineering over a period of six years (Fig. 1.9). The design has progressed through three basic systems with users involved at all stages. The tests have not involved a statistically large group, but vital information (both anecdotal and quantitative) has been fed back at all stages of the design process.

Initially a relatively cheap educational robot, the Atlas arm, was purchased to investigate the feasibility of what could be achieved with this level of technology. At the same time a survey was carried out of potential users. Trials were carried out to investigate different interface options for directly controlling a manipulator, initially using a two dimensional computer simulation, then a selected three options controlling the Atlas arm. The educational arm, controlled by a home microcomputer, formed the basis of a system tested with 5 volunteers. These tests proved the feasibility of the use and control of a robot arm by the severely physically disabled.

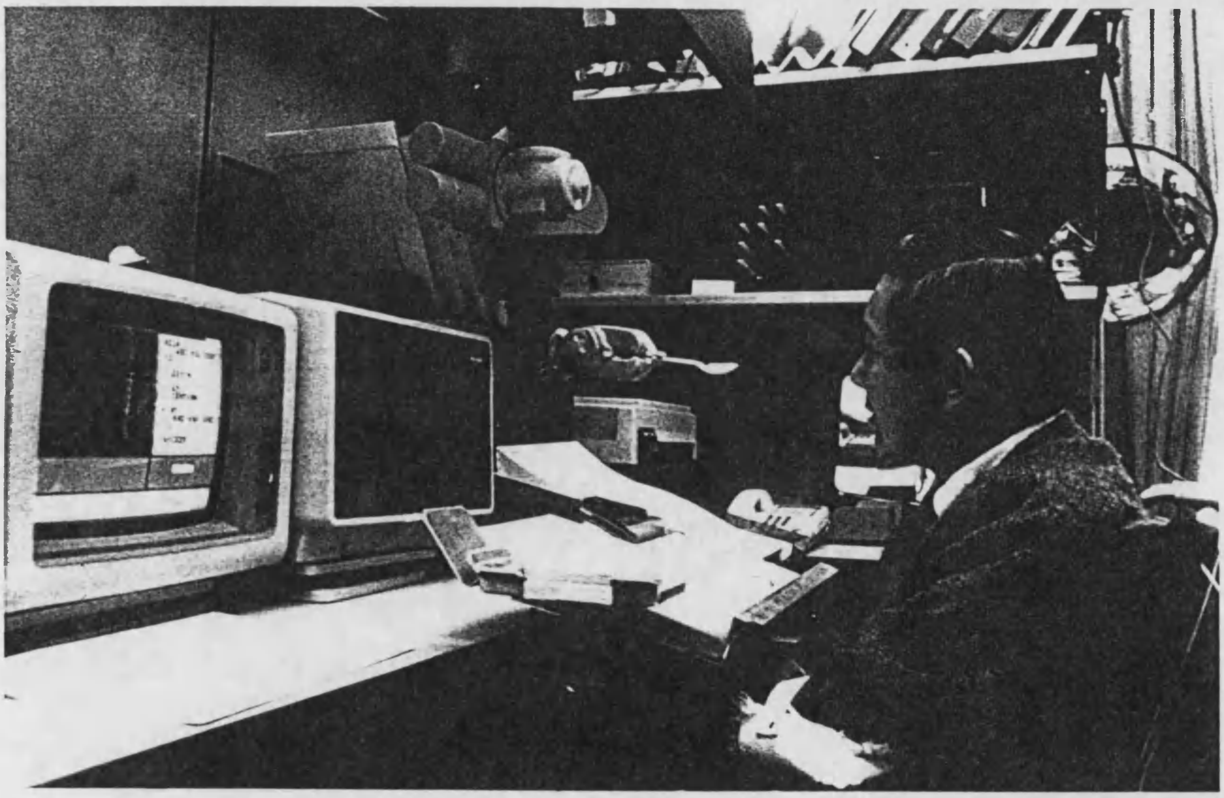
The next system integrated the same Atlas arm into a workstation, with various tasks arranged around the arm. This system underwent trials at the Spinal Injuries Unit, Odstock hospital. A questionnaire was carried out on those who had used the robot system.

From experience with the Atlas based workstation the general quantitative specification for a relatively low powered arm was confirmed. However the need for a better layout was established. With the valuable support of the Wolfson Foundation a low cost arm was developed in-house, integrated into a workstation. Brief initial trials with this system received a favourable reponse to the improvements made. A number of modifications were suggested to the user interface. More extensive trials were carried out at Odstock Hospital, and then for a period in the home of a potential user.

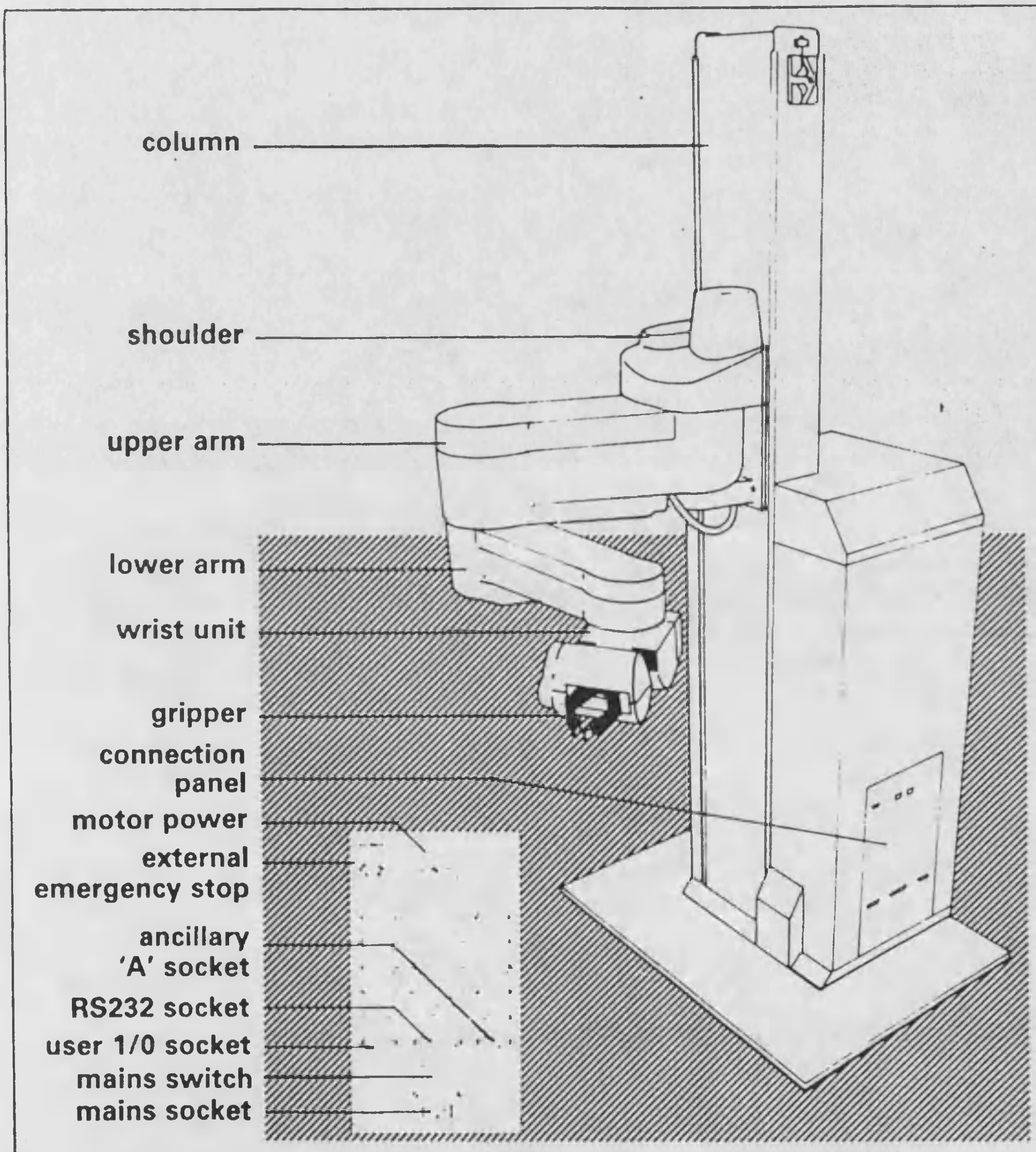
For the future, the most appropriate application areas for such a robot system are being considered, with the likelihood of a redesign of the arm for low volume production. The possibility of mounting the arm on a wheelchair is also being considered.



Johns Hopkins University workstation Fig. 1.1



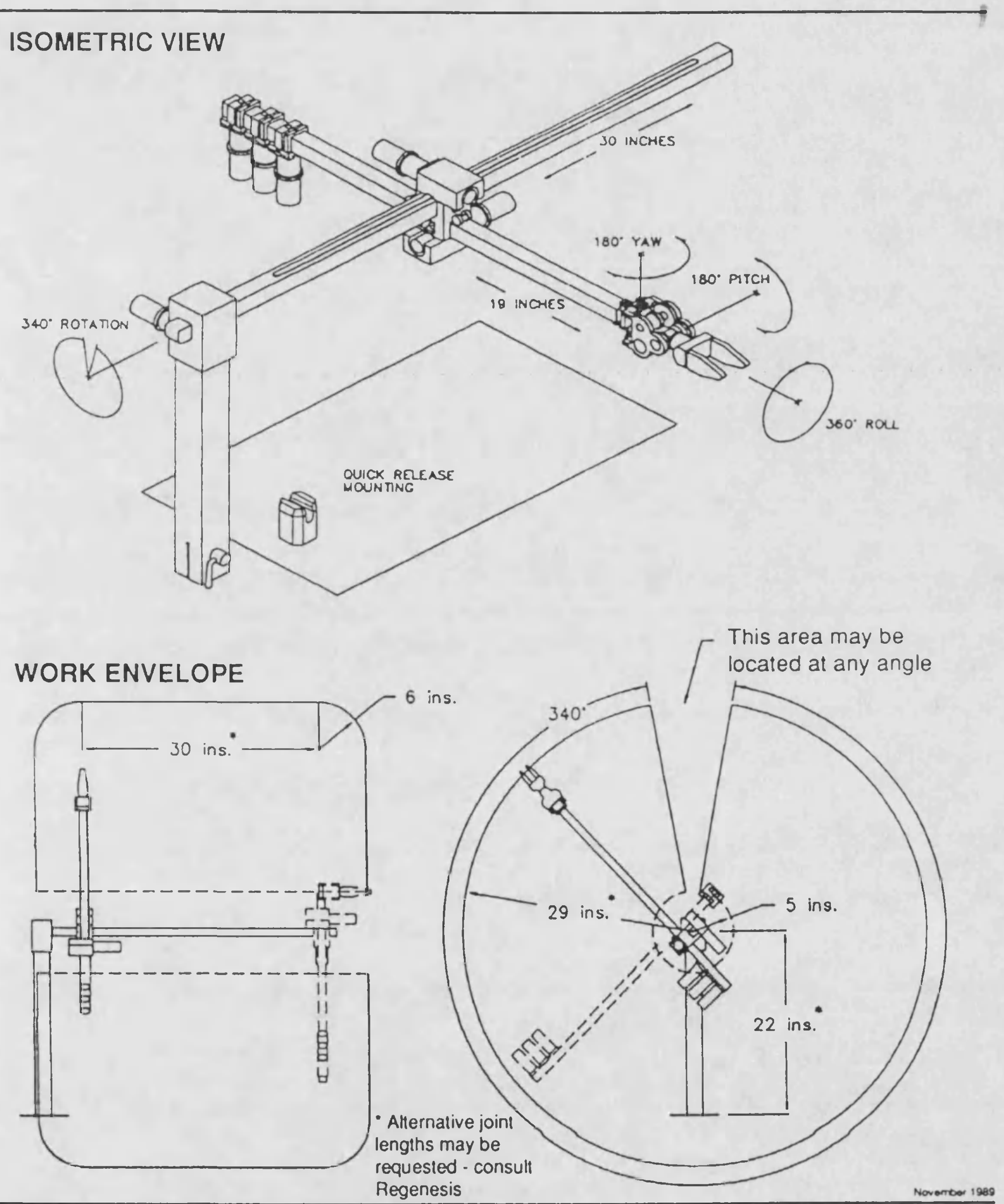
Stanford University/VA DeVAR IV workstation Fig. 1.2



The RTX robot arm components

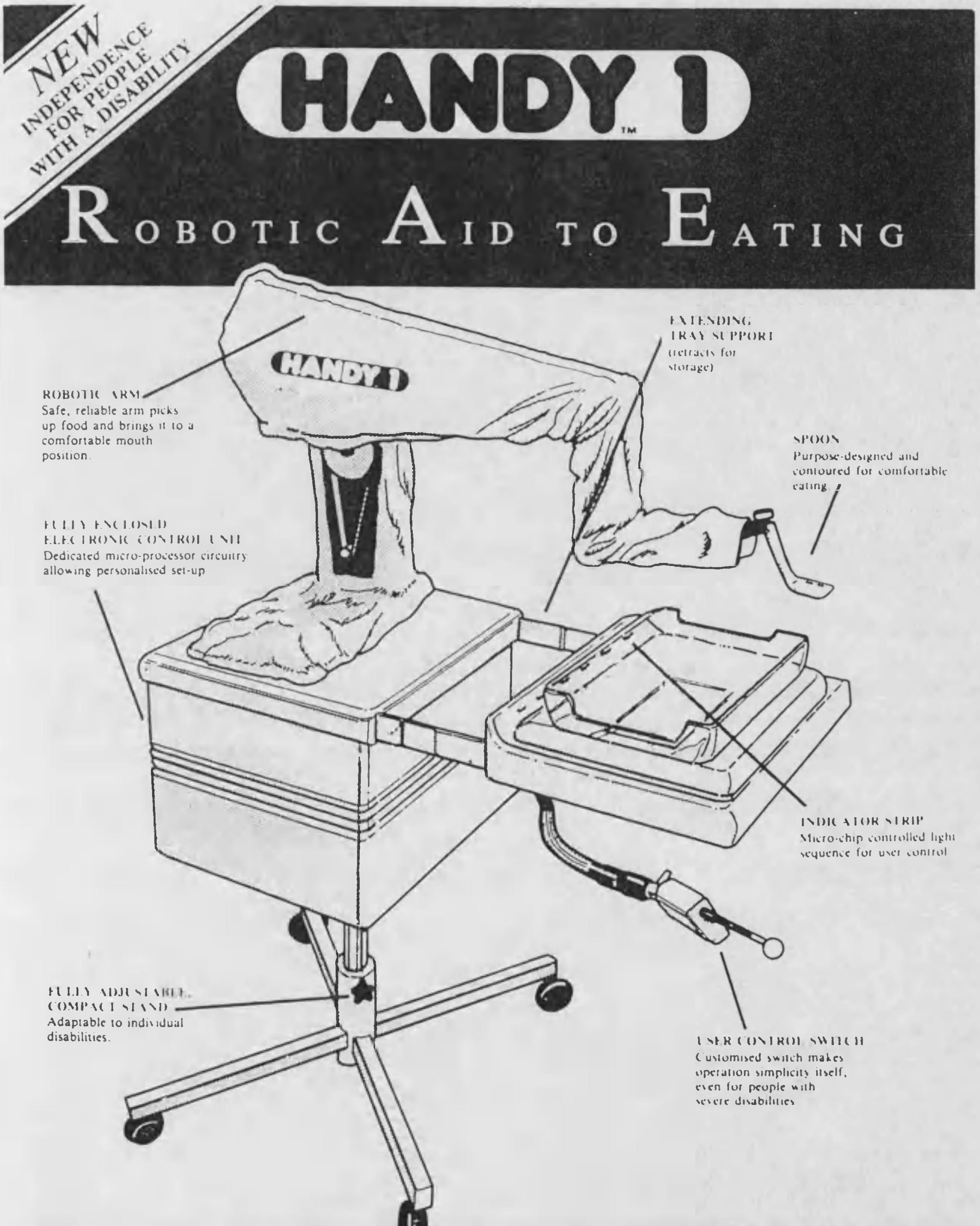
UMI RTX robot arm — Fig. 1.3

Regenesis Robotic Workstation Attendant

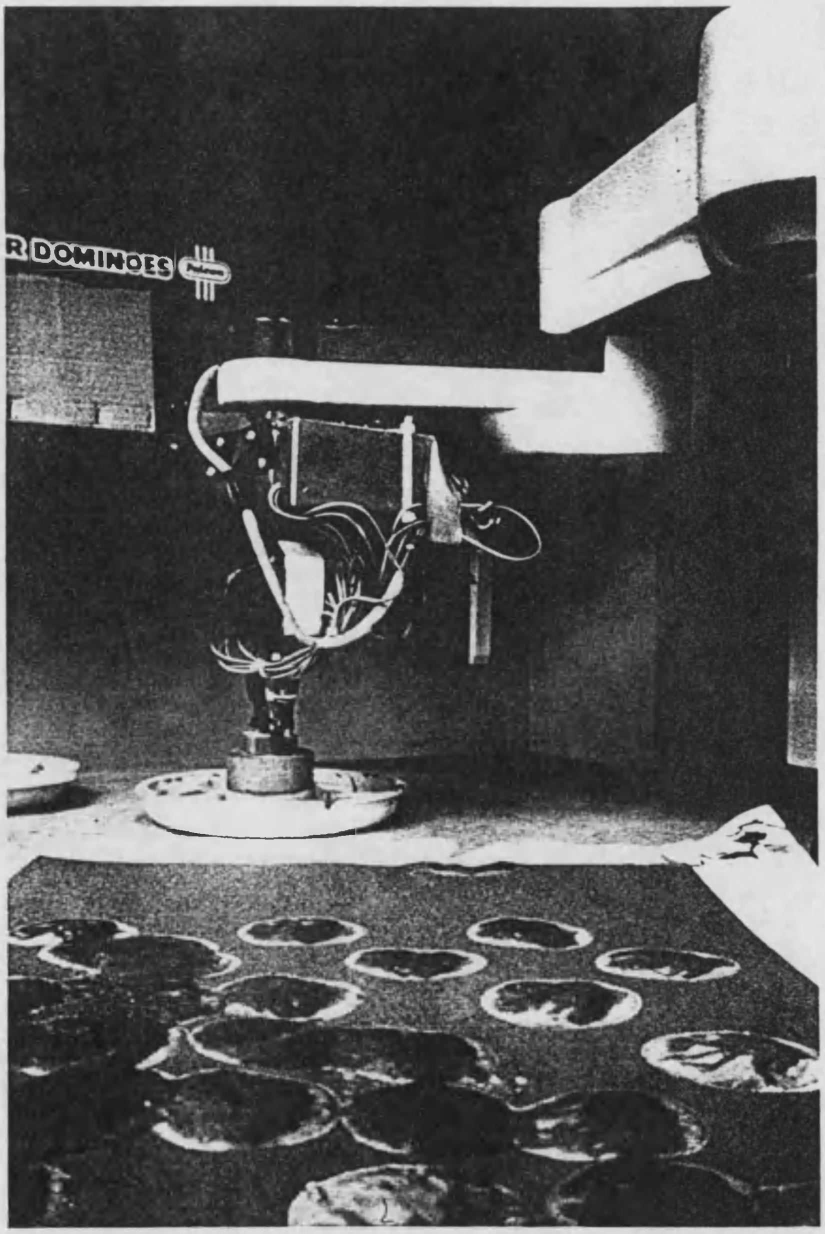


REGENESIS Development Corp. 1046 Deep Cove Road, North Vancouver, B.C., Canada V7G 1S3 Tel: (604) 929-6663 Fax: (604) 929-3316

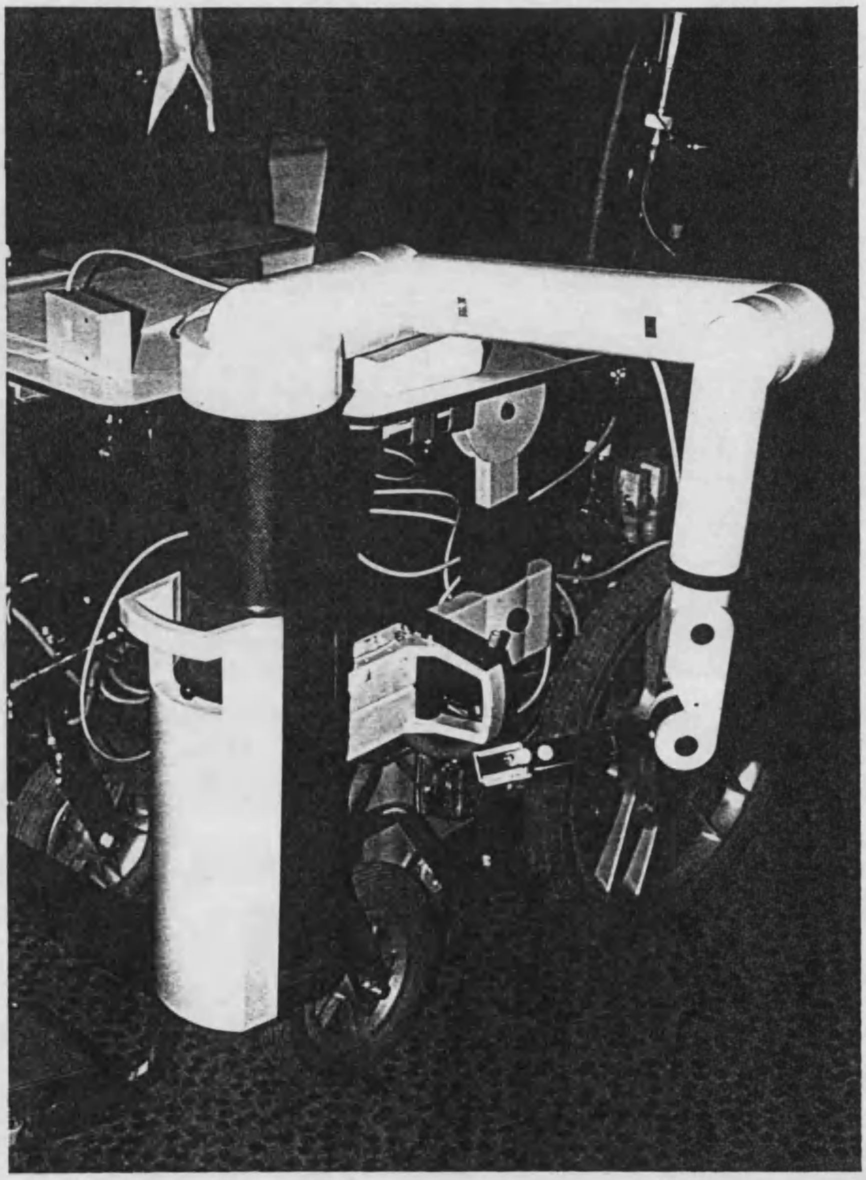
Regenesis Robotic Workstation Attendant — Fig. 1.4



Keele University "Handy 1" aid to eating — Fig. 1.5

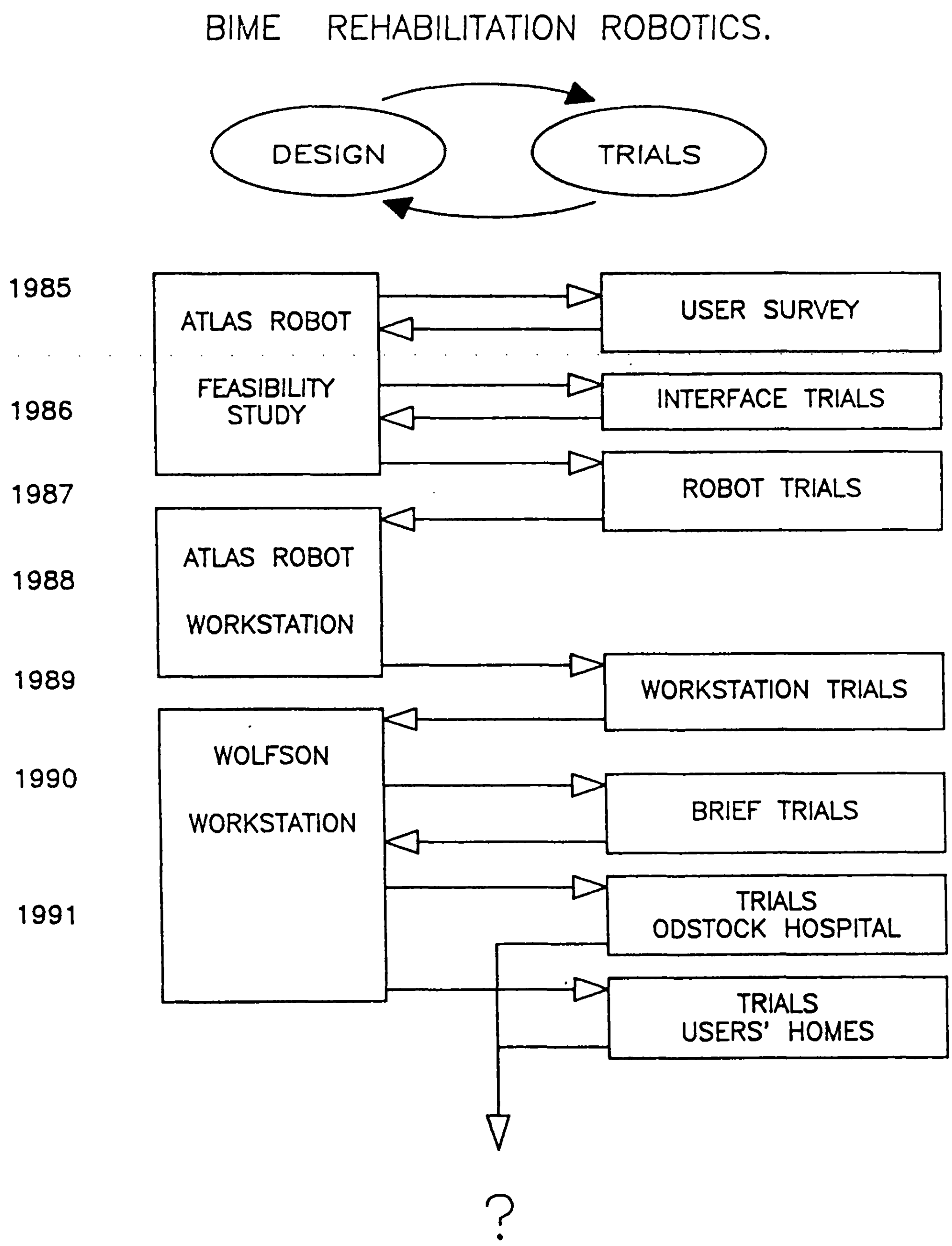


Cambridge University educational robot system Fig. 1.6



Manus wheelchair mounted manipulator   Fig. 1.7

Stanford University/VA MoVAR mobile robotic aid   Fig. 1.8



Overview of BIME Rehabilitation Robotics Fig. 1.9

Chapter 2. SURVEYS OF POTENTIAL USERS.

INTRODUCTION

Early in the project a survey was carried out of potential users to determine the needs, abilities and situations of disabled people. A subsequent survey, by Prior of Middlesex Polytechnic, is also discussed. The chapter ends with a discussion of the potential market size for a rehabilitation robot.

BIME USER SURVEY

Forty two subjects were interviewed in the Bath area - all of these people had limited or no upper limb ability. The subjects were in the age range 16 to 65 and were divided 27 male, to 15 female. 25 had multiple sclerosis, 10 had spinal cord injuries, 3 had spastic paresis, 2 had rheumatoid arthritis, and 1 each had motor neurone disease and transverse myelitis.

The domestic situation of people will have an effect on the type of tasks which a robot may be required to perform. 45% were married and living at home, 9% were single or widowed and living at home, 17% were married and living in a hospital or institution, and 29% were single and living in an institution (Fig. 2.1). Of those living at home the vast majority (82%) were living in a detached or semi detached house. It is useful to generalise that those in an institution would have little need or desire for a robot, while of those living at home, those with a carer would require robotic help to give them an extra degree of independence and to relieve their carer of some of the burden. A much smaller percentage (9%) were living at home relatively independently. This number could be increased if comprehensive aid was available from a robotic system.

The survey covered the tasks which people were or were not able to do, and aspects of their daily lives. Of the 42, only 3 were in any type of employment, in each case on a part time basis at home. Two were accountants while the third used an electric knitting machine. The average daily time spent watching TV was 4.1 hours, and 1.3 hours per day reading. 25% had hobbies, including CB Radio and stamp collecting.

Questions were asked about various tasks which people might need to do. Some were able to carry out the tasks unaided, while others only with difficulty or with an aid or not at all. The majority were not able to carry out tasks in the kitchen, all tasks requiring some manipulation, but the majority were able to operate various electrical devices.

Further questions covered the physical ability of people to move various parts of their body. It was found that all the subjects would be able to use a two switch input device (for example microswitch, suck/puff switch), and seven were familiar with this as a form of input for the control of an environmental control unit. All but five of the subjects were able to use a joystick, and many were familiar with this as a means of controlling an electric wheelchair.

Those interviewed were asked what types of tasks a robotic aid might be used for in their situation. The replies were:

Making a hot drink
Feeding
Picking up items from the floor
Kitchen use
Loading a cassette
Plug things in
Moving hot things
Opening beer cans
Load a video
Play chess
Using a telephone
Eating fruit
Brushing teeth
Washing
Watering plants
Smoking cigarettes
Pouring coffee from a percolator.

Having completed the questionnaire, 60% of the subjects felt that a system would be of some practical use to them, but only 43% said that they would seriously consider buying it. The other 17% agreed that it would be of use to them but felt that the cost (then quoted as £2000) was too high.

PRIOR USER SURVEY

Subsequent to our survey a similar survey was carried out by Prior of Middlesex Polytechnic [58]. His survey targetted users of electric wheelchairs as potential users of a wheelchair mounted manipulator. Of a survey size of 50, the majority were found to be living at home, rather than in a care institution. Of those living at home the majority were with a family or partner. This suggests a heavy burden placed on the families of disabled people if they are able to live at home. Of those of working age 79% had no paid employment.

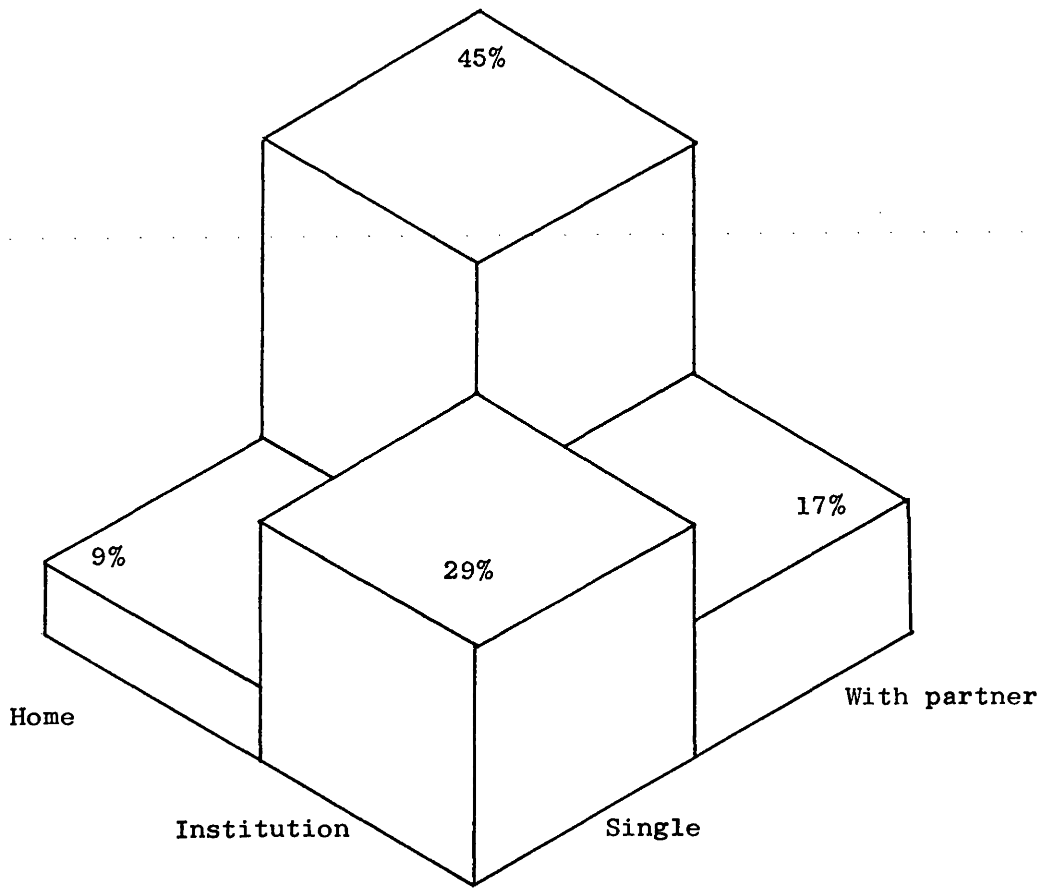
Those surveyed were asked whether they were able to perform a range of tasks in the areas of personal hygiene, domestic, leisure and recreation and working environment. Finally the subjects were asked to suggest the top 5 tasks which they would like to be able to perform. The most popular choice was reaching, stretching and gripping, the second was gardening, followed by reaching the floor, cooking and feeding. These results are similar to our own.

MARKET SIZE

The viability of a rehabilitation robot system from a commercial point of view is related to the potential market size. A survey from the Office of Population Censuses and Surveys [59] gives a total number of disabled adults in the UK of 5,780,000. Of these approximately 890,000 have severe disability of the upper limbs, restricting reach, stretch and dexterity. Disability is defined in the report on a scale of 1 to 10. We have taken a level of 7 to be the appropriate level for potential users of a robot. This level is defined as not being able to raise either arm above the head and being unable to pick up either a small object such as a pin or a heavy object such as a pint of milk. If we consider those who are of an employable age (and also more likely to accept technological aids) the number is still 225,000. Of these 206,000 are living at home and 19,000 in communal establishments.

Prior, in the survey referred to above, quotes a UK population of 20,000 to 30,000 electric wheelchair users, while Van der Loos [60] quotes a US population of 60,000 tetraplegics. These figures, while indicating maximum numbers, do not account for the appropriateness of people's situations nor whether they would wish or accept such technological assistance. Finlay in a nore extensive market survey [61] includes the elderly, and estimates an annual UK market of approximately £2 million per year.

Cost is a major consideration in the final acceptance of devices. At Stanford University [62] the cost of their vocational system is justified on the basis of cost saving in attendant care, estimating that their system, priced at over $50000, could pay for itself in a few years. This approach is particularly relevant when the costs are being paid by an insurance company. However it is difficult to quantify the overall financial benefits of a robot system. When funding comes from government departments, the provider of the capital is not the same as the department which makes the savings. The cost of a feeding aid for children is more difficult to justify in purely financial terms. The approach at Keele University has been to raise charitable income in order to provide their Handy 1 aid free of charge.



Variation of place of abode with marital status of disabled people.

Fig. 2.1

Chapter 3. INITIAL INTERFACE TRIALS

INTRODUCTION

A major area of concern in rehabilitation robotics is the man machine interface. The problem is quite different in many respects from that encountered in other areas of robotics. Individuals who are disabled and may benefit from a robotic aid have limited control ability to instruct a robot.

In parallel with the development of the robotic hardware, preliminary trials were carried out to determine an appropriate interface. Initially a user interface was implemented to control a two dimensional computer representation of a robot. Secondly a smaller number of interface systems were tested with the robot programmed to make very simple movements. This led to the selection of a symbolic scanning menu for the main trials with the robot.

APPROACHES TO MAN MACHINE INTERFACE IN ROBOTICS

One major distinction between different interface systems is between analogue and digital methods. Conventional analogue input devices include joystick, mouse and tracker ball. These may be appropriate for disabled users either in standard form or modified. Two dimensional input may be either used to drive a robotic manipulator in an analogue fashion (as a joystick) or to point to an object in a menu (as a mouse).

Digital input methods may either use a scanning menu system, a coded system, an array of switches or voice control. For those with the ability to control just one or two switch inputs, scanning menu systems are often used. The input devices used include light action hand switches and switches operated by the foot, head, chin or other parts of the body. Other types of switch used include suck/puff switches, electromyograph (EMG) inputs and eye operated switches. Since the choice of switch is very dependent on the individual user, a robot system must be arranged such that a range of switches should be available to be plugged into the control input, and software parameters should be adjustable.

The initial priority in developing the interface for the control of the robot was that it should be usable by the most severely physically disabled with very limited control ability. For this reason interfaces based on a scanning menu system were evaluated. Simple joystick interfaces were also evaluated for those able to use such an input. Though voice control may also be used by the most severely disabled such systems were not considered appropriate for direct control of a manipulator.

TWO DIMENSIONAL COMPUTER REPRESENTATION.

Nine different user input interfaces were tested using a purely computer based test system. On the left of the screen a two dimensional computer representation of a robot arm was displayed, and on the right any instructions were displayed similar to that illustrated in Fig. 3.1a. For the nine systems tested the following parameters were varied.

Input device: The basic input used was a two switch device used to control a menu of some kind. One switch was used to scan through the menu, and the other to select from the menu. A variation of this was a single switch scanning system where a cursor scans through the menu at a predetermined rate, and the switch selects the option required. The other input device tested was a two dimensional analogue system, either a joystick or a roller ball.

Representation of menu: The simplest representaion is to have a textual list of options (Fig. 3.1a), the options being movement directions, such as right/left, up/down. Alternatively the robot may be represented by a simple diagram with the direction of motion marked by arrows on the diagram (Fig. 3.1b). The cursor scans between the arrow symbols. (If an analogue input is used the cursor is positioned over the symbol). The third system is to have a symbolic menu (Fig. 3.1c) where the directions are represented by arrow symbols in a simple list.

Movement directions controlled: The Atlas robot which we were to use moves in a vertical plane by extension and elevation of the arm. The arm may be controlled therefore either by controlling each motor, or by controlling the end of the arm in cartesian coordinates. A further variation of this is to set the cartesian coordinates either aligned with the axes of the work area, or aligned with the axes of the gripper.

The variations tested are listed in Table 3.1. Initially the first five systems were tested, and the remaining four were added on the basis of experience.

Test no.	Input	Menu representation	Directions controlled
1.	2 switch	Text	Work space axes
2.	2 switch	Pictorial	Motor rotations
3.	2 switch	Pictorial	Work space axes
4.	1 switch	Text	Work space axes
5.	Analogue	Pictorial	Work space axes
6.	1 switch	Pictorial	Work space axes
7.	2 switch	Pictorial	Gripper axes
8.	2 switch	Symbolic	Work space axes
9.	1 switch	Symbolic	Work space axes

Table 3.1 Input tests - variations tested.

Each subject was asked to direct the "arm" to pick up the "ball" represented on the screen. In order to quantify the results the following measurements and timings were made.

Total number of selections made

Time the arm was actually moving

Thinking/selection time

Total time for task

The tests were conducted in two parts. The first were with 16 able bodied volunteers, who each tested two of the input systems. The second part was tests with disabled users, who used whatever input system was most convenient to them.

Tests with able bodied users.

Each of the sixteen volunteers used two of the first five input systems. By comparing the results relative to a baseline it was possible to calculate a percentage improvement (or worsening) for each system. Since there is obviouly a learning process, the order in which different systems were tested was varied for different people. Seven attempts were given on each input system (as well as a short initial period of familiarisation before timed tests were started).

The results of the tests are summarised in Fig 3.2, all related to input system 1 as a baseline.

In Fig. 3.2a it is seen that the least selections (ie the most efficient movement, or the least mistakes) was for the pictorial representation either with a two switch or an analogue input. Compared with these the control by individual motors was worse, and the single switch system was worse still.

In Fig. 3.2b it will be noted that there was very little difference in the time for which the arm was moving. This is to be expected, as the input system only affects the users performance, and not the performance of the arm. In general the same distance has to be moved whatever the input system.

Figs. 3.2c and 3.2d illustrate the time taken to make the selections and the total time taken. Single switch control is seen to be no better or worse than double switch (Tests 1,4). The use of the pictorial menu (Tests 2,3,4) was quicker than the use of a text only menu.

Overall the following recommendations may be made.

Workspace axis control is better than individual motor control.

A 2 switch system or an analogue input causes less mistakes than a single switch system.

A pictorial representation is better than purely text, though a scanning pictorial menu is confusing since the cursor doesn't move in a single logical direction.

Tests with disabled users.

Tests were carried out with 16 disabled users, mainly in local Cheshire Homes (as these homes provided a high concentration of users in one place, rather than going to the homes of individuals). Input devices were chosen for users depending on their physical ability. For the two switch input either a large Possum microswitch was used or a suck/puff input. Although timings were taken it was not possible to analyse these results in the same quantitative fashion as it had been for the tests with the able bodied volunteers. Very few of the volunteers were able to complete tests for more than one input system. This was partly due to physical disability and partly due to limited concentration and lack of familiarity with computers. It is recognised that choosing volunteers from residential homes rather than from those living in the community was an unfortunate choice, since they were in general less motivated.

However the qualitative observations were very useful. It was particularly valuable to note the problems which the disabled users had in operating a simple switch, and modifications were noted for future use. One particular problem was that there was a tendency to keep the hand on the switch, rather than releasing it after a selection had been made. Another similar problem was that of hand tremor, leading to a false double selection. At this stage the symbolic menu was introduced, which proved to be very effective.

TESTS USING ROBOT

On the basis of these tests the following input systems were chosen for further tests with the actual robot.

1. Pictorial representation of arm, with analogue input. (Fig 3.3a).

In the earlier tests a pictorial representation was used with a scanning menu. Although a pictorial menu was effective, its combination with a scanning system was problematic, since the cursor did not move around the screen in a logical fashion. It was decided that the best way to use a pictorial representation was with an analogue input. The cursor is positioned over the appropriate direction arrow using a joystick or roller ball, and the movement is started and stopped by the use of two buttons. The joystick was not self centering. One problem with a flat representation of the arm is that it is difficult to represent movements out of the plane of the screen, though a 3-D sketch might allow better representation of such movements.

2. Symbolic representation of arm, with analogue input. (Fig. 3.3b)

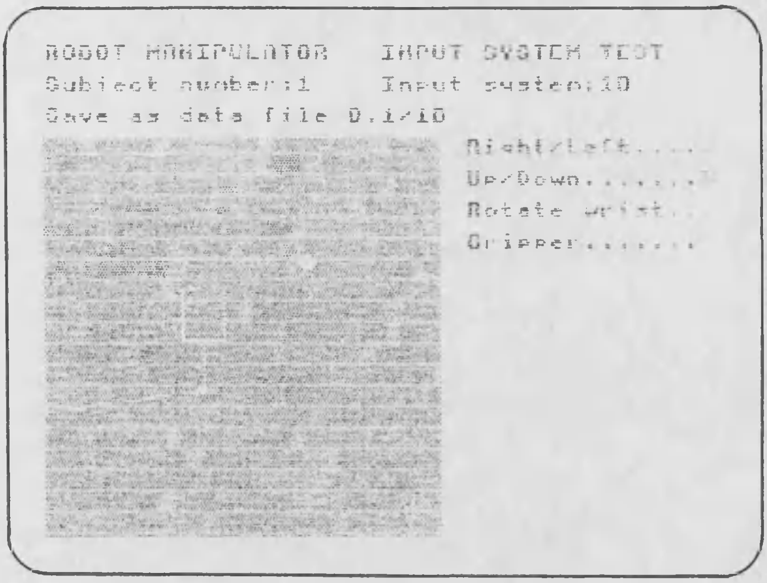
Since the symbolic representation proved very effective it was combined with an analogue input. This was done by splitting the screen in two, with the upper half representing the arm, and the lower the gripper/jaws. Since only two degrees of freedom can be represented on a plane, the third degree of freedom for each half of the screen is represented by text (eg In/Out). Movement is controlled as in 1. above, with the joystick selecting the movement, and two switches being used to stop and start the motion.

3. Symbolic menu with double switch input and
4. with single switch input. (Fig 3.3c)

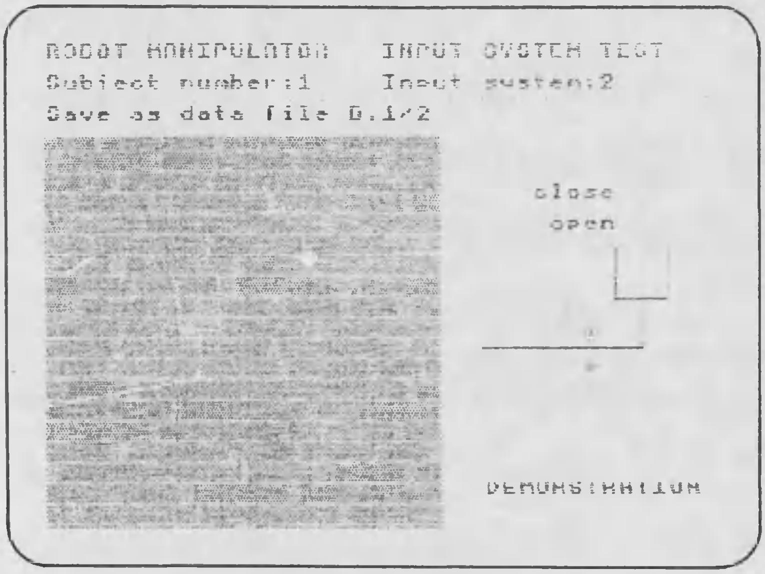
The symbolic representation was used with both a two switch and a single switch input. The choice between these two inputs will be made on the basis of the ability of the user. However some users who would have been able to use a two switch input found the one switch input easier. The reason for this was that with the two switch system there was an uncertainty over which of the switches should be pressed. Also disabled people with partial use of only one hand found it difficult to move the hand from one switch to the other

These systems were chosen in order to use the best of the screen representations with a range of input devices for a range of abilities of users. Perhaps the most logical use of an analogue input is for direct piloting of the arm. However this method of control demands a degree of dexterity which most of the disabled users visited did not have. Therefore, although this method was set up for use in the laboratory it was not tested with disabled users.

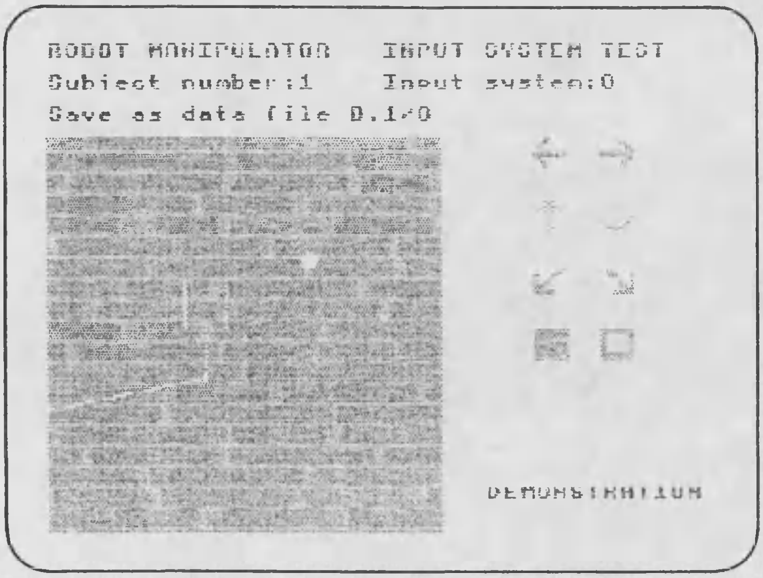
These systems were tested with a number of users, both disabled, and able bodied volunteers. Only qualitative results were obtained. For the disabled users the analogue input was difficult to use. Therefore for further tests it was decided to use a scanning system with either single or double switch input, with the main emphasis being on the two switch input. Option 3 was therefore chosen. This choice however does not preclude the use of other systems in future. For any generally available system it is important that a number of user control methods should be available.



a. Text Menu



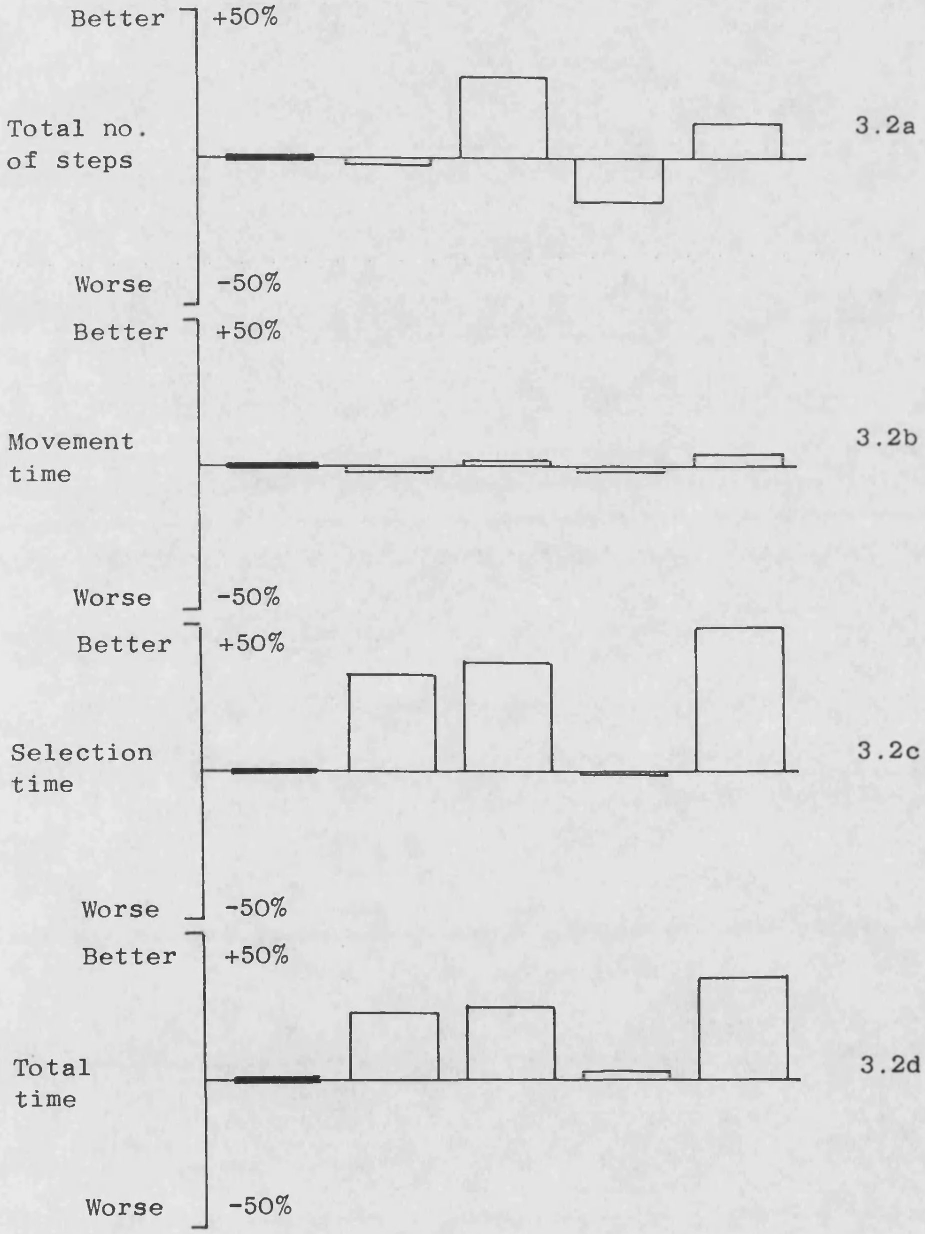
b. Pictorial menu



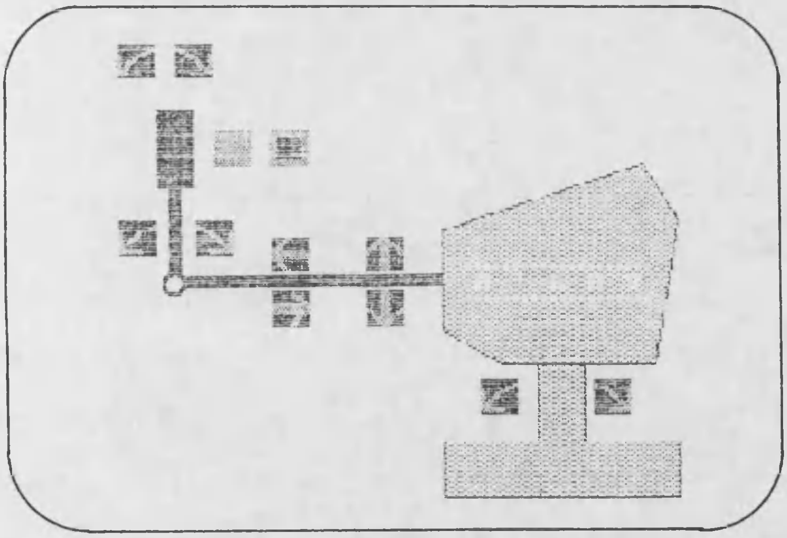
c. Symbolic Menu

Screens used for 2-D robot input tests. Fig. 3.1

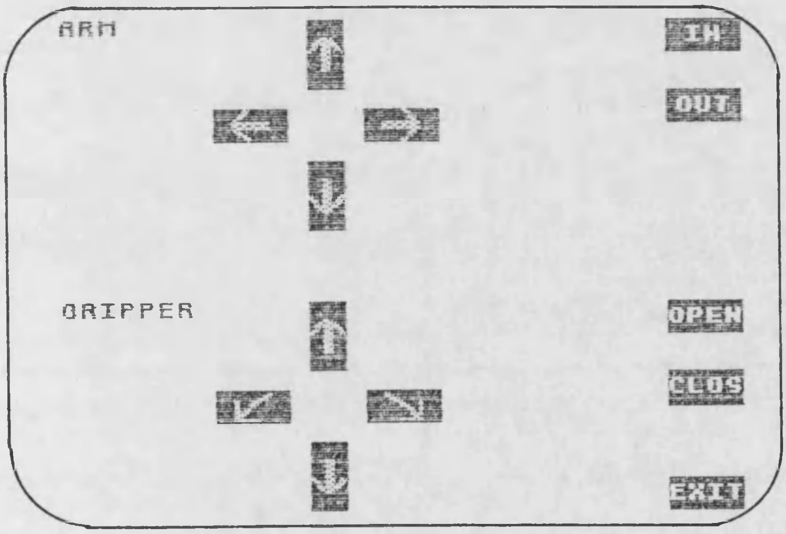
Test no.		1	2	3	4	5
Input	2 SWITCH	O	O	O		
	1 SWITCH				O	
	ANALOGUE					O
Menu	TEXT	O			O	
	PICTORIAL		O	O		O
Axes	WORKSPACE	O		O	O	O
	MOTOR		O			



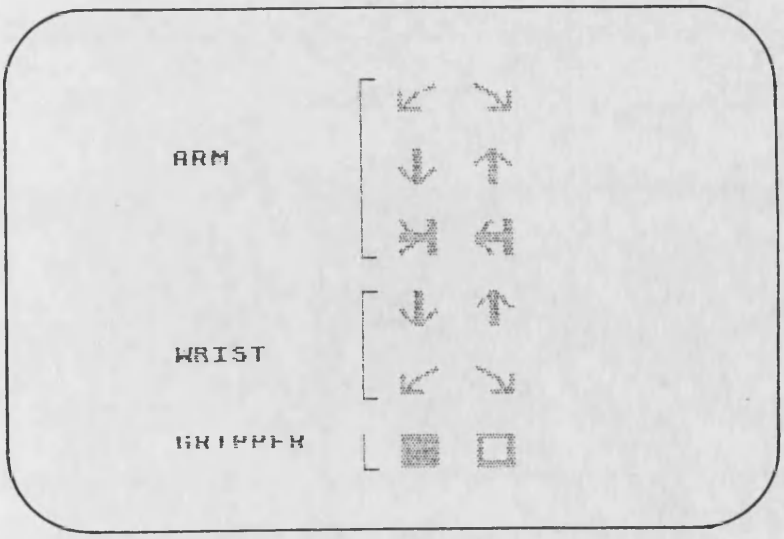
Relative performance of different input systems. Fig. 3.2



a. Pictorial display
(Analogue input)



b. Symbolic display
(Analogue input)



c. Symbolic display
(Switch input)

Screen displays for different robot control methods. Fig. 3.3

Chapter 4. FEASIBILITY STUDY SYSTEM - TECHNICAL DESCRIPTION

INTRODUCTION

The specification for the feasibility study system was based around the use of a commercially available robot arm. The Atlas arm used was essentially unmodified, with the exception of the gripper. A jig was constructed for storage and to aid manipulation of objects. Parallel communication between a microcomputer and the robot utilised a simple interface based around a pulse generator circuit. Software was written in a combination of assembler and BASIC. The software modules incorporated a user interface, software to handle the user switch input, and robot control software.

SPECIFICATION

The first practical part of the work was to set up a system using available hardware which could be transported to the homes of potential users to gain experience of the tasks which might be carried out and the software and hardware required. It also enabled the disabled people to see what sort of system was being proposed (many still think in terms of the robots of science fiction) and therefore to comment more realistically on the concept of rehabilitation robotics.

It was decided to use and adapt a commercially available robot arm for the initial feasibility study, rather than to attempt to design and build one.

The specification at this stage was therefore to use a commercially available arm. The cost should be less than about £3000 (allowing most of the educational arms to be considered). Load capacity should be adequate for domestic tasks, at approximately 1kg. Accuracy and repeatability should both be approximately 1mm

User input to the system should be by a two switch input device through a scanning menu sytem on a microcomputer.

This approach reduced the cost and development time considerably, and experience with this feasibility study system has allowed a more accurate specification to be formulated for later stages in the project.

MECHANICAL HARDWARE

The robot arm chosen was the Atlas robot (Fig. 4.1), intended primarily for the educational market. This arm is manufactured by L.J.Electronics of Norwich, UK. At around £2000 the Atlas robot is at the top of the educational robot price range, but it is considerably cheaper than any of the industrial robots.

It has five degrees of freedom, plus gripper open/close, all of which are stepper motor driven. All the motors are located within the "head" with the exception of base rotation. Drive is transmitted to the end effector degrees of freedom (elevation, roll and jaws) by means of rotating shafts. This gives a clean appearance to the extending arm, but the overall appearance was judged to be unattractive. This arrangement also made it difficult to incorporate major modifications to the gripper.

The arm movement is polar, within a spherical working volume. There is no yaw degree of freedom, which means that tasks can only easily be carried out if arranged radially around the arm. The configuration had good performance in terms of load capacity and rigidity. With a load capacity of 2kg it was able to lift a kettle of water, which was judged to be the heaviest load the robot would be required to lift.

The modifications made to the hardware of the robot were mainly to the gripper assembly. Referring to Figure 4.2, the rubber faced V-grooves in each jaw are for grasping cylindrical objects. Although it was decided to retain the parallelogram linkage of the standard Atlas gripper, the linkage was lengthened in order that the gripper would open wide enough to be able to grasp a standard mug. The wide end plates are for grasping flat objects, such as a cassette tape, while being thin enough to insert an object into a confined space. One of the flat end plates is extended back to the V-groove to resist the twisting of an object, such as the handle of a kettle when it is tilted or unbalanced. Finally the gearing of the wrist rotation was altered, since the torque available was found to be insufficient, when rotating a large unbalanced object such as a kettle of water. (In practice it was subsequently decided not to attempt pouring a kettle of boiling water for safety reasons.)

A single degree of freedom two jaw gripper will always be limited in its manipulative ability and so simple jigs were used to assist. As illustrated in Fig. 4.3, a small rack unit was constructed for these feasibility tests. The rack held cassette tapes (removed from their cases) for insertion in a cassette player located underneath the rack. The top shelf of the rack could hold various items, including a spoon. Small pieces of sponge rubber were used to locate items in the rack, but yet still allow easy removal.

In order to make the best use of the flexibility of a robotic system it was intended to use unmodified equipment. One cheap and simple modification introduced however was a spoon for feeding. This was an ordinary dessert spoon with a bent handle, and a tube of polystyrene placed over the handle to make it easier for the robot to grip.

ELECTRICAL HARDWARE

The electrical hardware used for the feasibility study is essentially that built into the Atlas robot. This is illustrated in Fig 4.4.

As originally intended the Atlas is operated by a multi key "teach console", which is inappropriate for a disabled user. This teach console communicates with a built in microcomputer based around a 6502 microprocessor chip. Another built in facility for control is to build up a table of movements in an external microcomputer which is transferred via a serial link to RAM in the Atlas microcomputer. The microprocessor sends a parallel signal to the demultiplexer which controls each of the six motor drive amplifiers. Limit switches (either microswitches or simple metal to metal contact) indicate mechanical end positions and the demultiplexer board includes logic to stop the motors at these positions, and zero the counters.

As used in the feasibility study an external microcomputer replaced the Atlas microprocessor, communicating via a parallel link. The computer used was the 6502 based Acorn BBC Model B Microcomputer. The parallel signal which is required by the demultiplexer has a 3 bit code to select the motor, a motor direction bit, and a step pulse input to step the selected motor. Signals received back indicate if the selected motor is at either extreme of its travel. Two other lines are used to reset the arm to its home position (via the Atlas

Microprocessor).

The BBC Microcomputer communicates with the Atlas system through its User Port. The User Port has an 8 bit bidirectional data port, and two handshake lines. Originally the computer's internal timer was used to generate the pulses to step the robot. It was found however that this gave rough running of the motors. This was due to the fact that the BBC Microcomputer extensively uses interrupts for functions such as scanning the keyboard. Thus the computer's higher priority interrupts blocked the interrupts to pulse the motors and led to uneven timing.

In order to produce an accurately timed pulse a simple interface circuit was designed (Fig. 4.5) using a basic timer circuit. The timer circuit is based around a 555 timer IC in astable mode, running at a fixed frequency. The output from the timer circuit is gated with an enable signal from the computer to send a pulse to the Atlas. The enable signal is generated in an interrupt driven routine, triggered each time the timer pulses. The interrupt routine increases or decreases the motor step counter, monitors the limit switches, and sets up the motor control lines and enable line for the next pulse.

The method described above gives an accurately timed pulse. The overall speed of the robot is restricted by the time required for the interrupt routine. This restriction is more severe the more motors that there are running simultaneously.

SOFTWARE

The software is written in a combination of BBC Basic and assembler on the BBC Micro. The main user interface software is written in BBC Basic, making easiest use of the graphics facilities and being easily modified. Three separate assembler programs create the necessary machine code. The three sections of machine code deal with:

(a) The movement of the robot,

(b) Handle switch inputs from the user,

(c) Calculate the steps for a particular cartesian position.

Machine code was necessary for these functions because of the speed requirements and the need to use machine interrupts.

User Interface Software.

The basic user interface was developed during trials with disabled users very early in the project, and this development has been described above.

The disabled user uses a two switch input to control the robot system through a menu based computer interface. The input devices normally used in the tests were either a small microswitch unit or a suck/puff switch, connected to the digital input lines of the Analogue/Joystick port of the BBC Micro. The microswitch had the two switch positions marked RED and BLUE, and in the description below this nomenclature is used though in practice it might be suck or puff.

The menu system can be described by the tree structure shown in Figure 4.6. When the program is initially loaded and run the user is presented with a main menu (Fig 4.7a) containing options to move the arm, replay a procedure, create a procedure, to move to the start position or to end. Options are selected by using the BLUE switch to scan through the list of options and the RED to select.

If the option to move the arm is selected, a screen as in Fig. 4.7b is shown. BLUE is used to scan down the list and select the appropriate motor or vertical/horizontal motion. When the cursor covers the appropriate motion, the RED is used to scan between the two opposite directions of motion. If either of the two directions of motion is selected, pushing the BLUE will then move the arm. For as long as the BLUE is pushed the arm moves in the required direction, stopping when the switch is released. When RED is pushed a new motor may be selected. The flow diagam for this menu is given in Fig. 4.8. A different method is used for a suck/puff switch, namely that BLUE will start the motion and RED will stop it. This method is necessary since it is not easy to sustain a long suck or puff.

The other major control option is to replay a procedure from memory. A number of procedures were programmed into the software code, and in addition three user defined procedures may be stored on disc.

The "Pour" option enables a container to be poured in such a way that the lip or spout remains stationary in space. A simple rotation of the wrist is not adequate. The correct motion of the various motors are calculated by reference to generalised shape parameters for a mug, a jug and a kettle. These are selectable by the user.

"Shake" is a procedure (used in conjunction with feeding) to briefly shake the arm to remove any drops from the end of a spoon.

"Stir" is a similar procedure which moves the gripper backwards and forwards three times for stirring a drink.

The "Feeding" procedure is more complex and enables the arm to be used for eating soup, or more solid food, from a bowl using a spoon. For each feeding session the system has to be set up by the user driving the arm directly, firstly to the bowl and then to the his or her mouth. Thereafter the procedure continues between bowl and mouth with the minimum of user intervention. The only user control required is to adjust the position of the spoon over the bowl (important if solid food is being eaten). The spoon pauses at the user's mouth and a signal is required to return to the bowl when the user is satisfied.

User defined procedures allow the robot to be driven through a series of predefined points. The procedures can be set up by the user or an assistant by selecting the "Create Procedure" option. The user then moves the arm through the required motions. At appropriate positions a "pause" can be inserted so that on replay the motion will pause and allow the user to make fine adjustment of the position. When the motion is complete the user is prompted as to whether he wants to save the procedure or not, and if this is confirmed the procedure is named by selection of letters from a 2-D alphabetic matrix (again using a scanning system) and is saved to memory.

The final option on the overall menu, is to move the arm to its start position. This drives all the motors to their reset positions. Limit switches, when triggered zero the motor counters. Finally the wrist is moved down to a horizontal position.

Switch Control Software.

The software to process the switch commands from the user is kept separate from the menu and motor control software. This has been done primarily so that changes can be made to tailor the switch control to the particular user, without changing the main program.

The switch control software makes use of the BBC's event handling facility. Using the "update screen" event, an event can be triggered every 1/50 sec to check the state of the switch inputs.

Routines are provided to enable the switch inputs to operate in three distinct ways.

1. Direct control in which the user directly controls the arm, starting and stopping as required. For an initial short period the arm will move at a slower speed, to aid precise positioning.

2. Replay of preprogrammed motions, but allowing the user to pause or stop the movement, for example if there is an unexpected obstacle.

3. Control of the user interface menus.

The switch software may be set up for the physical requirements of the user. The parameters which may be varied include a delay to compensate for user tremor, delays for auto repeat if the switch is held down, and the ability to turn on or off the computer generated "beep".

For direct control of the robot there are two main options
- The robot will move for as long as the BLUE is depressed. Releasing BLUE will pause the robot till BLUE is pressed again. Pushing RED will stop the arm and return to the menu.
- The robot will move when the BLUE switch is depressed and continue until the RED is pressed. (This is particularly used when a suck/puff switch is used.)

Other motor control options which may be set, depending on the physical ability of the user are for the initial "stepping" delay period, during which the arm moves at a reduced speed, and the maximum speeds of the motor

Control of robot movement

Control of robot movements is based around an interrupt routine. This routine is entered whenever a pulse appears on the interrupt line, set by the external timer circuit (described above in the hardware section). At the same time as the BBC Micro is interrupted, if the the motor on/off line is enabled, a pulse is sent to the robot to step one of the motors. The User Port is set up for the next pulse. The motor number and direction are set and the motor on/off line is enabled or disabled as required. This action is illustrated in the timing diagram Fig 4.9, where two steps of motor "0" are required for 1 step of motor "1".

The action of the interrupt routine (Fig 4.10.) is to increase or decrease the motor counter, check the position counter, check the limit switch status and to set up on the User Port for the next pulse, the motor number, direction and motor on/off line. The speed of each motor is determined by an 8 bit motor rate counter. Each time this counter decrements to zero the motor on/off line is set to "on" and the counter is reloaded from a latch. The speed is thus inversely proportional to the value held in the latch. More precisely the motor rate is equal to the external timer rate divided by the number of motors and divided by the motor rate value. On this basis the maximum motor rate is one sixth of the timer rate. In order to improve the speed motors are set "active" only as required and so for single motor movement the rate may be as high as the external timer rate.

The motors of the arm can be driven in four basic modes:

a) A single motor under the direct control of the user, using the control switches.

b) Straight line movement in the vertical plane, under the control of the user.

c) Movement of a single motor between two defined points. The only direct control from the user is to stop the motion if required

d) Movement of more than one motor between two defined points.

Of these four modes of movement, movement with a single motor is trivial when the correct parameters have been set up and the interrupt routine enabled.

There is a more complex procedure for the control between two points when more than one motor is involved. The reason for this is that only a limited number of speed ratios can exist between different motors (since the speed can only be an integer between 0 and 255) while the ratio of steps required between different motors is much wider. This is handled by changing the speed of each of the motors part way through the movement.

Movement in a straight line was found, in the earlier tests, to be the easiest means for direct control of a robot manipulator by the user. The facility to make straight line motion in a vertical plane was therefore provided. Straight line movement in a horizontal plane is not appropriate due to the lack of yaw freedom. For straight line motion in a vertical plane with the Atlas geometry it is necessary to run three motors simultaneously. These motors are arm elevation, arm extension and wrist elevation. Straight line motion cannot be created by a simple or constant ratio of motor speeds. The basic method used is to approximate the straight line motion to a series of moves between points a small increment apart. While the individual points are on a precise straight line, the path between the points is undefined. Due to the limited range of speed ratios available the motion through these defined points cannot be precise.

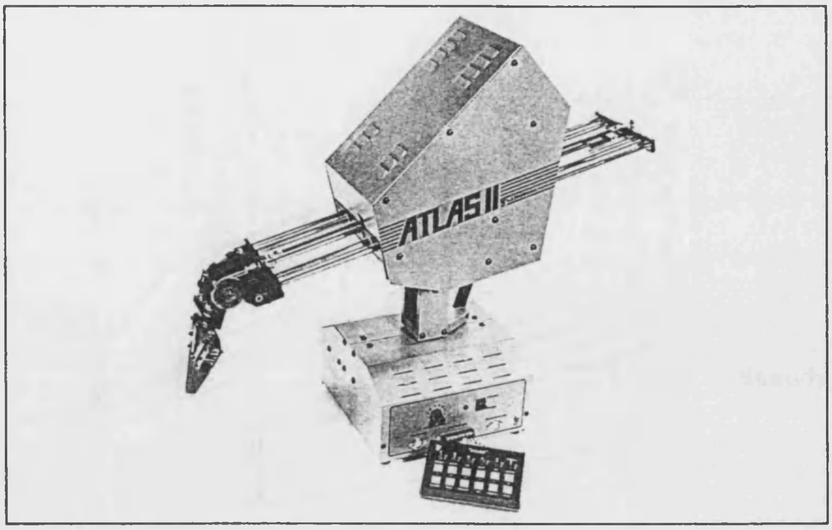
It is necessary to calculate the inverse kinematics for the manipulator, that is, the required steps for the arm elevation and arm extension motors corresponding to each r,z point (radius, height). This is performed by the third section of machine code, using a look-up table.

<u>Cartesian position calculation software.</u>

When the arm is controlled to move in a straight line in a vertical plane (keeping the wrist horizontal) it is necessary to know the relationship between the r,z Cartesian position and the number of motor steps for the arm elevation, arm extension and wrist elevation. In theory this could be achieved using a trignometric calculation. In practice however this is not possible since the calculation must be done in real time. Trignometric calculations are relatively slow which is a problem with a 6502 microprocessor. Moreover it is not possible, for the Atlas geometry, to derive a simple analytic expression to relate the cartesian position to the number of motor steps because of the arm elevation mechanism used.

In order to perform the calculation adequately quickly, look-up tables are used. In the tables the motor steps for the arm elevation and arm extension respectively are tabulated against r,z positions. Motor steps are tabulated for r,z position in one inch increments in each direction. A simple linear interpolation is used to find the number of steps for a required r,z position. A simple polynomial approximation is used to calculate the wrist position, for a given arm elevation.

Floating point arithmetic is used to calculate the interpolations in the look-up tables. Floating point arithmetic is not supported by the 6502 instruction set, and would be tedious to program. For this reason the program makes use of the floating point (and integer) routines in the BBC BASIC ROM. Entry points and conditions for these routines are provided in reference [63]



HSI ATLAS II Robotic System

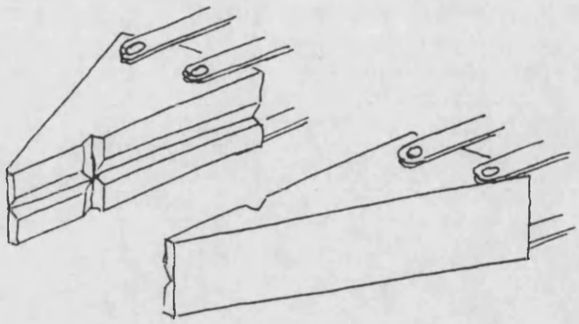
The ATLAS II is a polar type robot with 5 degrees of freedom, plus a supplementary gripper function. All the axes are driven by powerful stepper motors, with drive being actuated via toothed belts or gear mechanisms. The ATLAS II base contains an integral power supply and an on-board microcomputer. The unit is supplied complete with a hand-held teach pendant and parallel I/O adaptor board.

Maximum lift is 1kg, with a resolution of better than 0.1mm on all functions. Repeatability is better than 1mm on full load (0.5mm @ 1/2 load). Full limit switching with opto electronic sensors and microswitches is provided. This prevents any of the mechanical movements from being over-driven. This inherent mechanical accuracy makes the ATLAS ideal for use in a work-cell environment.

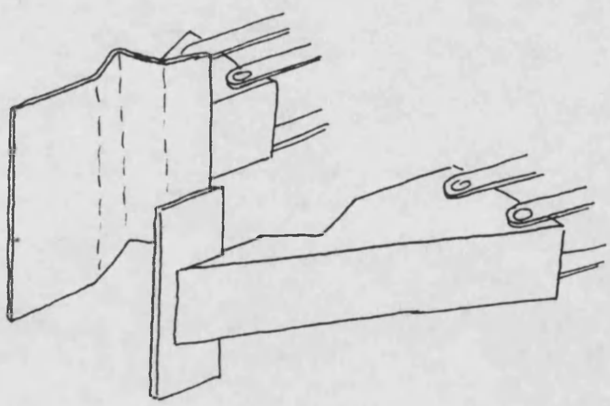
Mechanical movement specification:

Movement	Description	Speed of Movement (limit - limit)
Horizontal rotation	Driven by continuous toothed belt over cog wheels. Gear ratio for motor movement - 28:1	45° per second
Arm elevation 80°	Movement from 50° below to 30° above horizontal. Rack and pinion gear drive with 14 complete revolutions of the motor giving the 80°movement	26° per second through
Arm extension through 320mm	Driven by linear toothed belt. Gearing gives 12mm extension for one complete revolution of the motor	40mm per second
Continuous wrist rotation	Driven by shaft mechanism	102° per second
Wrist elevation 140°	Movement from 70° below to 70° above arm axis, driven by shaft mechanism	14° per second through
Jaws open/close maximum opening 50mm	Driven by a shaft/chain mechanism	From fully open to fully closed position in 4 seconds

Atlas robot details. Fig. 4.1



Standard gripper



Modified gripper

Gripper modifications - Atlas robot. Fig. 4.2

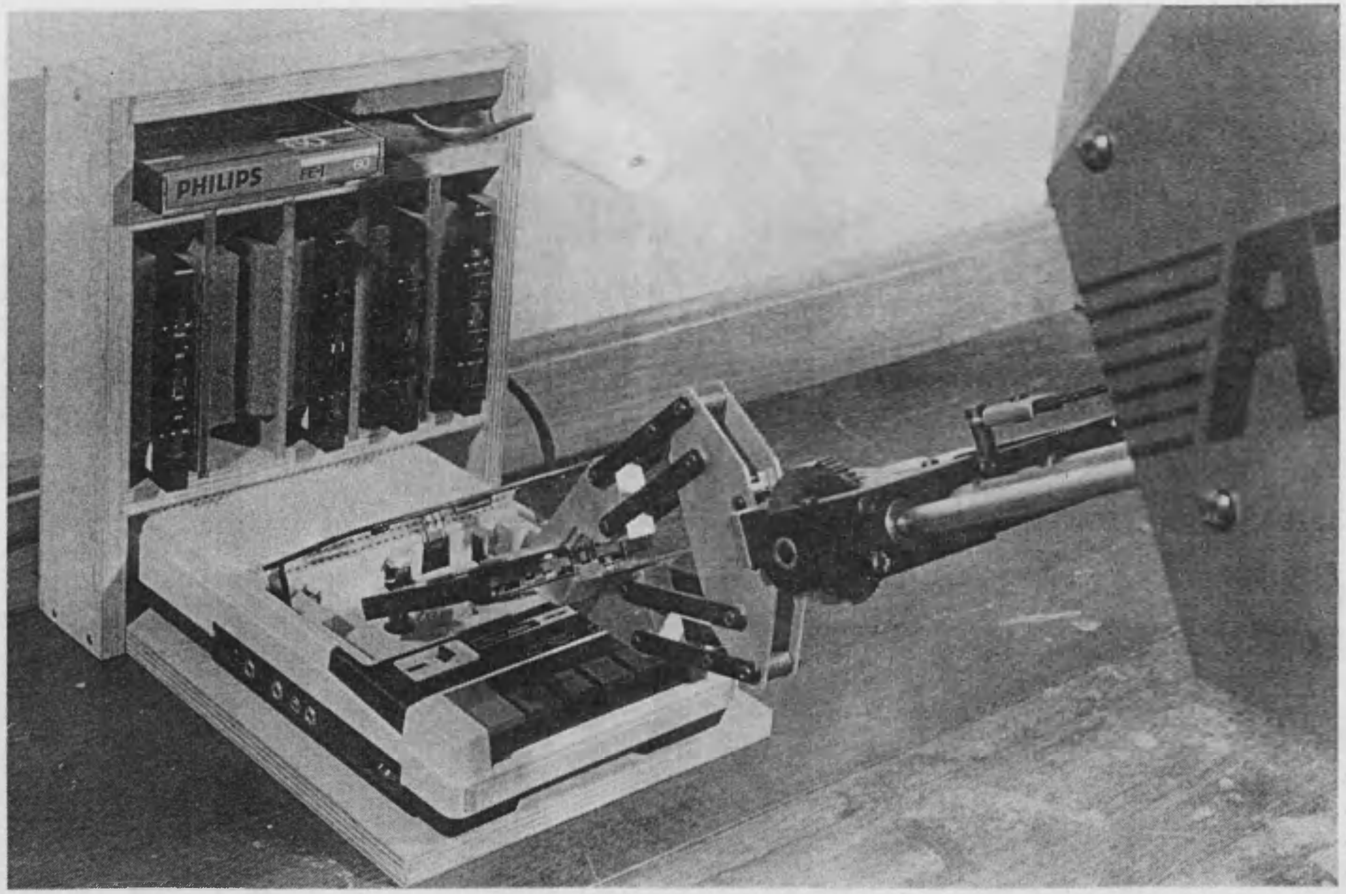
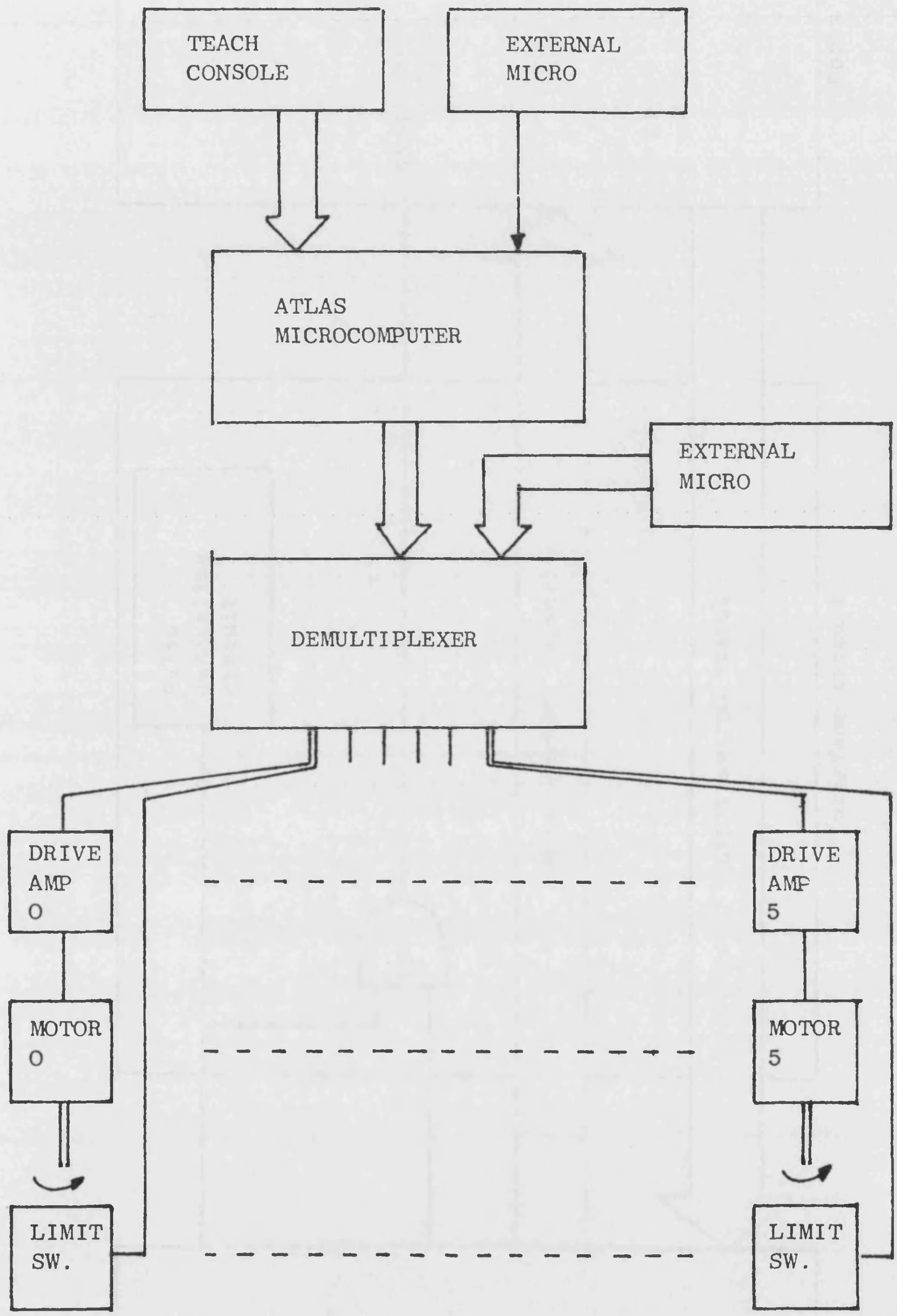
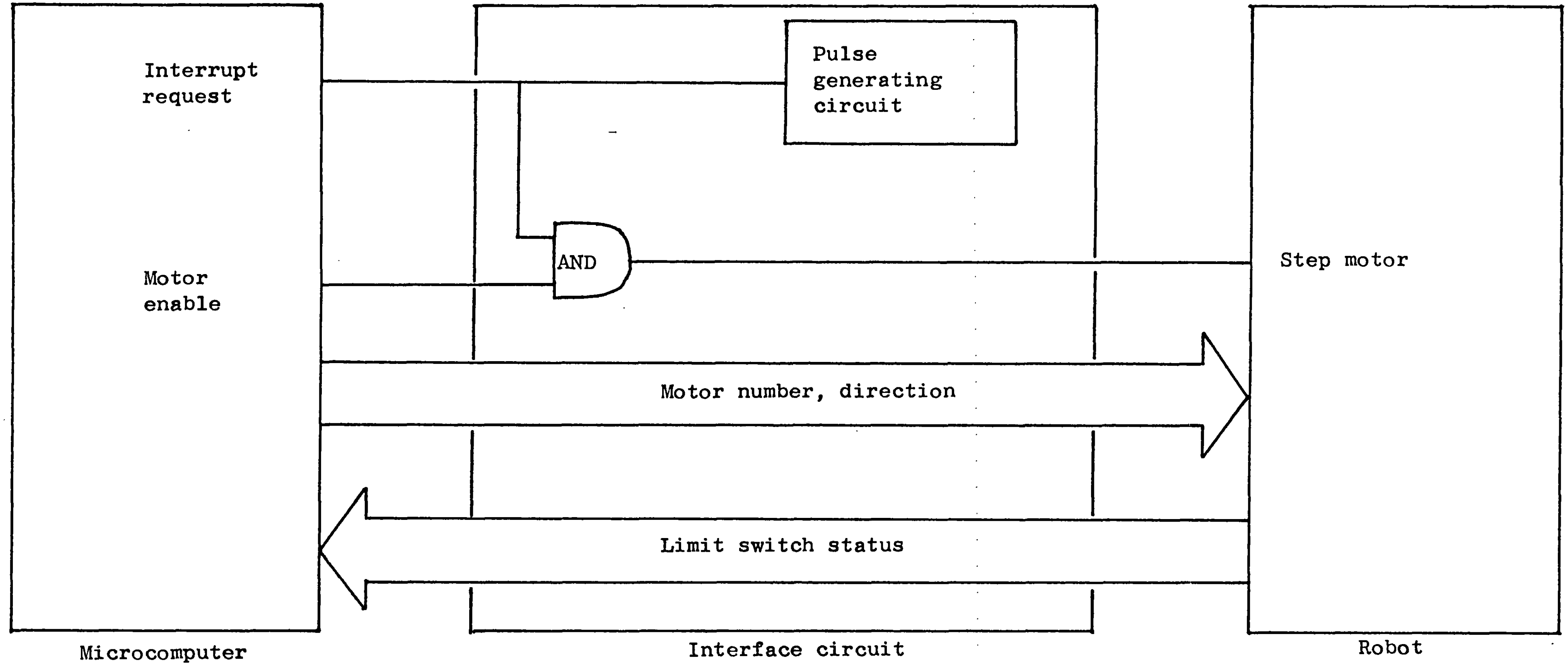


Fig. 4.3

Use of rack for cassette holding, etc.

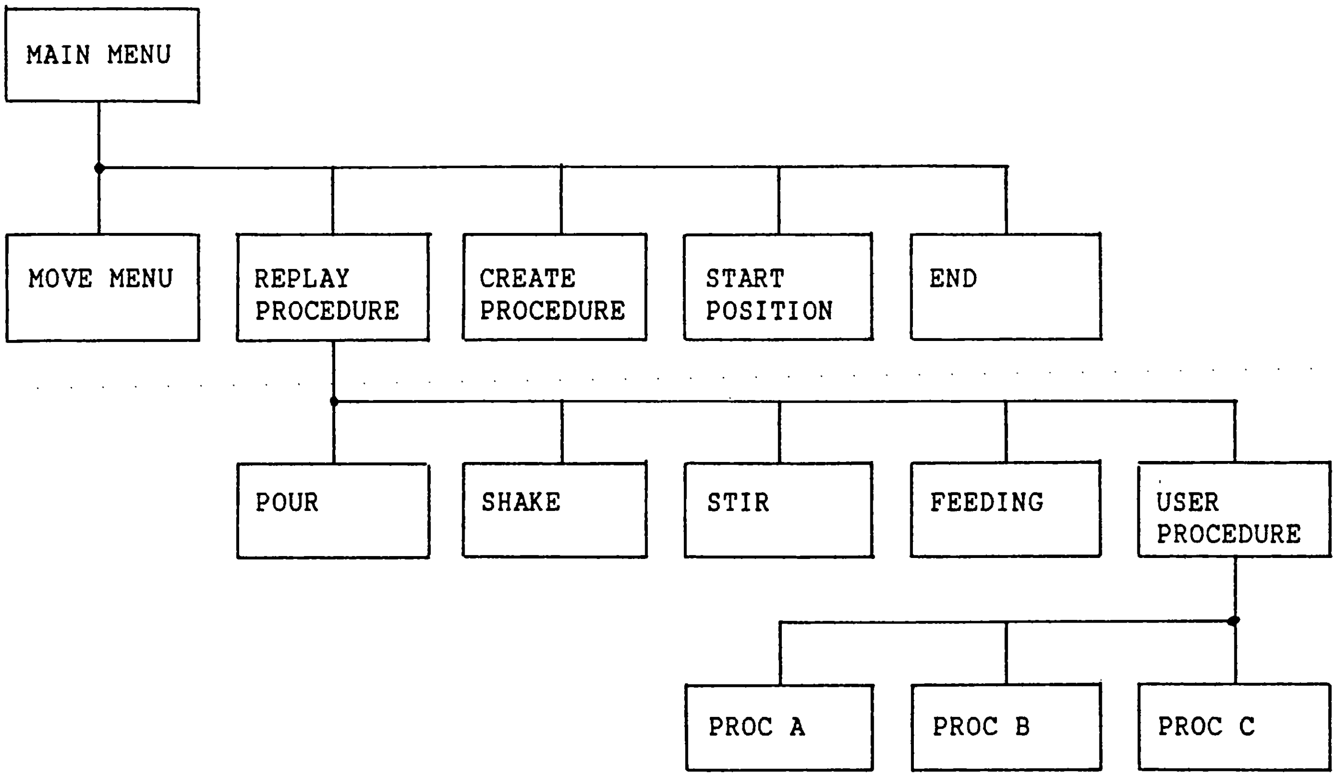


Atlas electronics block diagram. Fig. 4.4



Interface circuit for Atlas robot control.

Fig. 4.5



Overall menu tree for User Interface
(Atlas Feasibility Study) Fig. 4.6

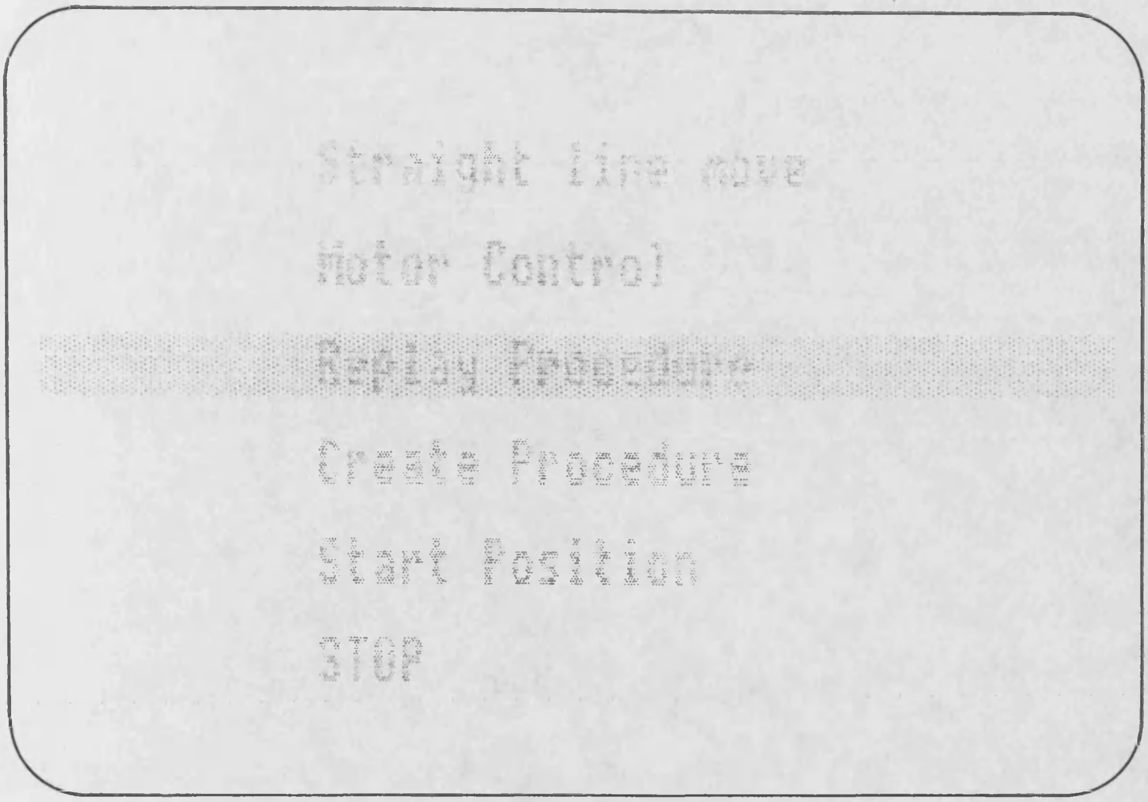


Fig. 4.7a Interface menu screen display

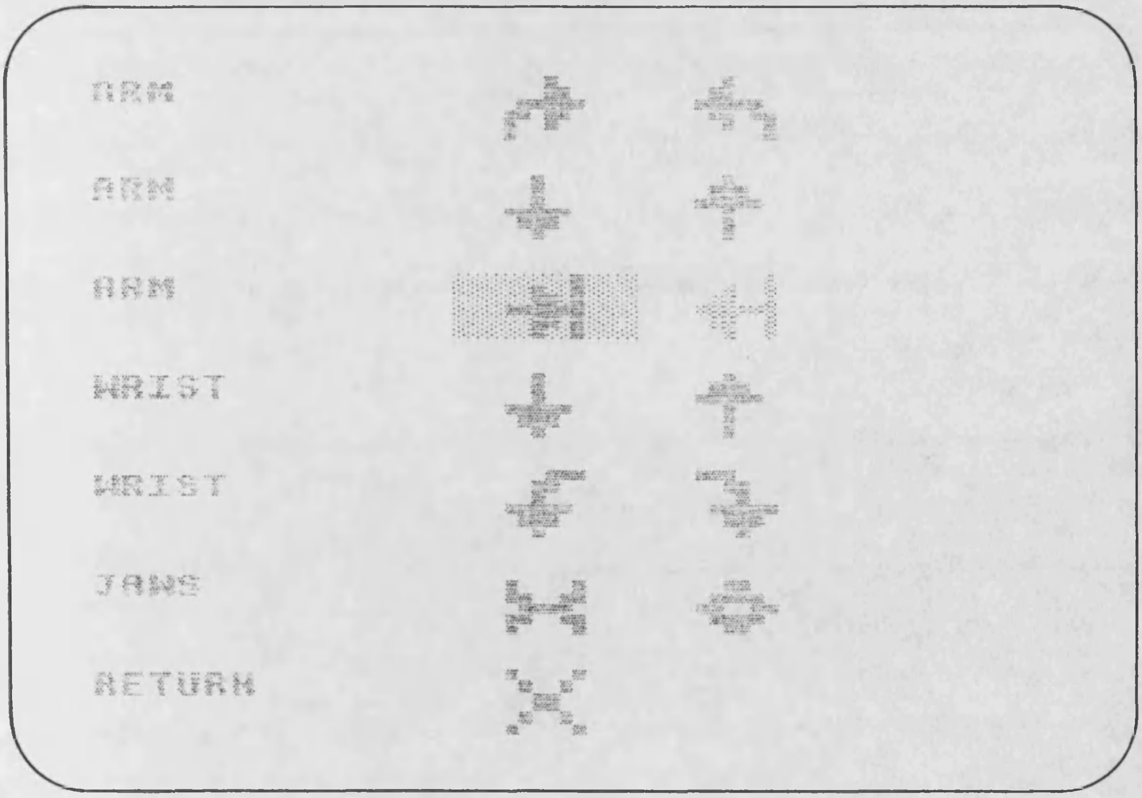
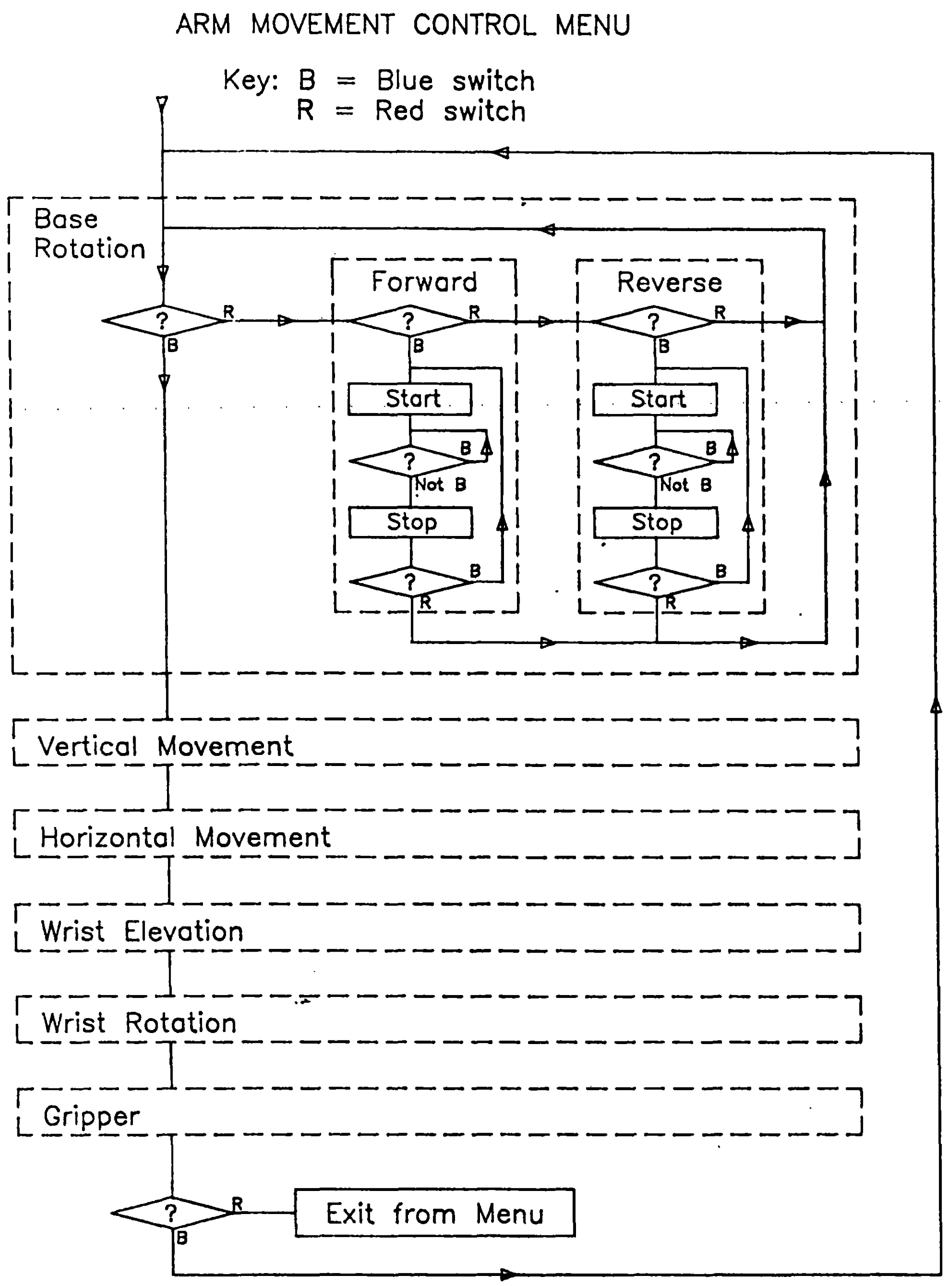


Fig. 4.7b Move menu screen display

Fig. 4.7



Flow diagram - Direct Move menu   Fig. 4.8

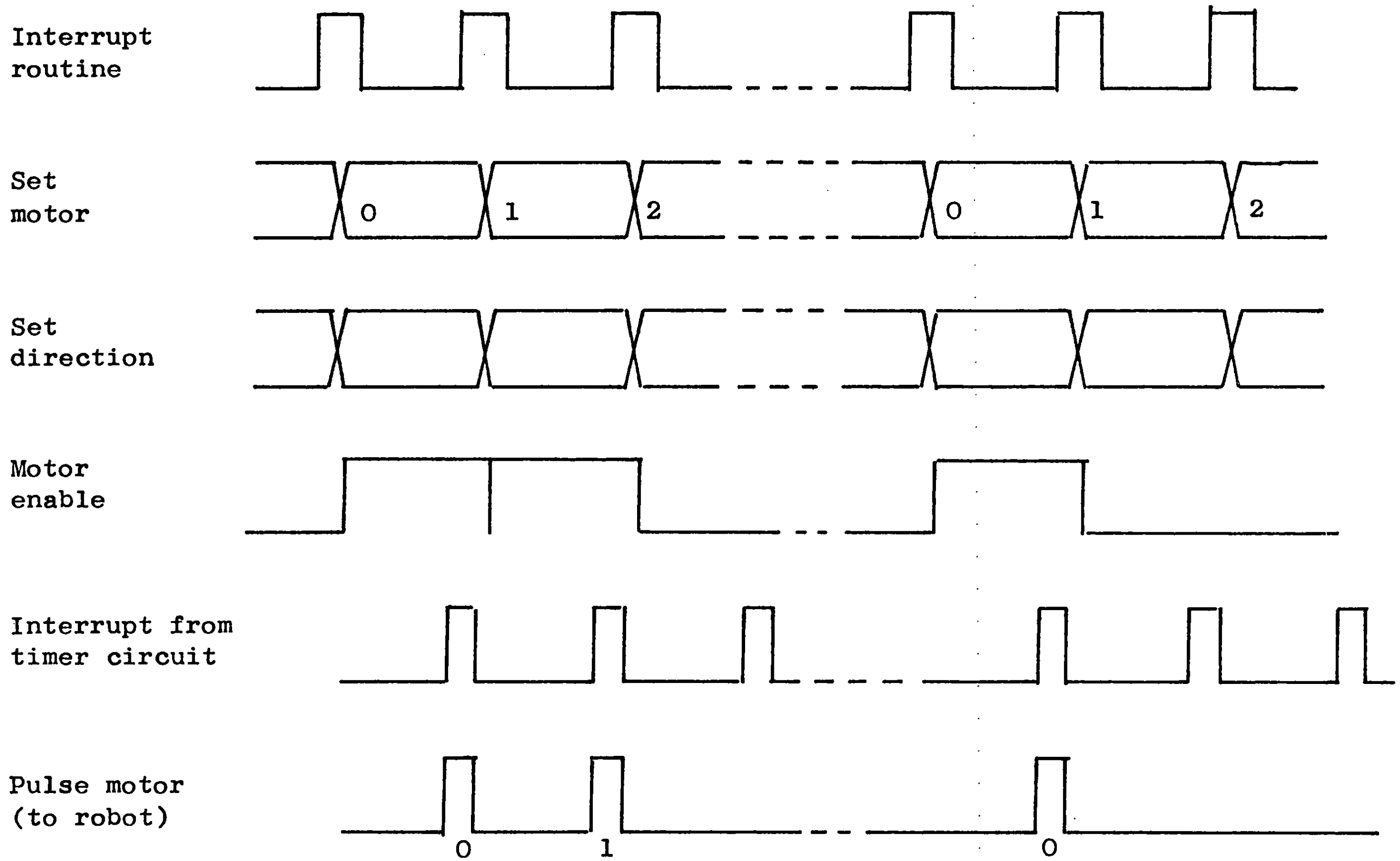
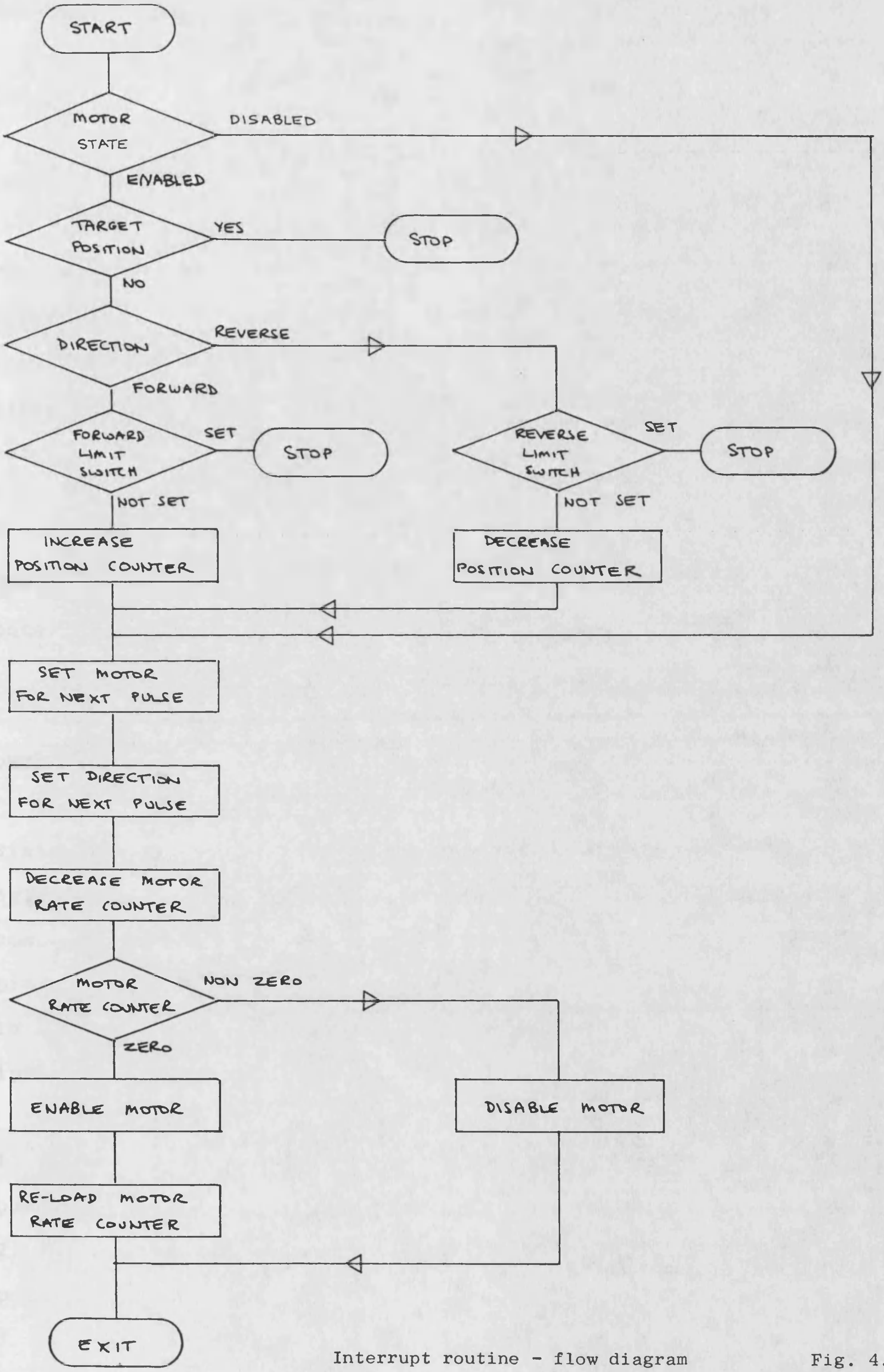


Fig. 4.9

Timing diagram for motor pulse control software / hardware.



Interrupt routine - flow diagram Fig. 4.10

Chapter 5. FEASIBILITY STUDY SYSTEM - USER TRIALS

INTRODUCTION

The robotic system was tested with five disabled people, either in their homes or hospital accomodation. Their reactions to the system are described under the headings of effectiveness, user input, mechanical configuration and safety. Further use of the system was explored by the author in a laboratory situation.

The conclusion was that a low cost manipulator does have potential to perform useful tasks for the disabled.

DETAILS OF SUBJECTS

Sixteen handicapped people, the majority of whom had originally been interviewed during the user survey, were contacted and asked if they would be willing to take part in practical trials with the prototype robot. Of those contacted, 10 were willing to take part in the tests. An introductory interview was carried out with the following aims.

1. To discuss the aims of the overall project and of the particular tests planned.
2. To determine the suitability and willingness of the potential user (and any carer) to take part in the tests.
3. To discuss possible tasks which might be appropriate to the

needs of the potential user.

4. To determine what input devices would be used. Particular note was made of any Environmental Control Sytems used, and the input devices used.

5. To determine the facilities and space available in the home.

6. To record details of the potential user.

7. To arrange for further visits with the robot.

At this stage a number of volunteers were discounted since they were considered to have sufficient ability not to be likely to benefit from the robot. None of the volunteers dropped out because they were unwilling to use the robot. Details of the five volunteers who used the system are as follows:

Initials: KW Sex: Male Age: 50
Disease: Multiple Sclerosis Length of time: ?
Previous occupation: Chartered accountant
Ability: Limited hand movement. Uses electric wheelchair
Accomodation: Adapted private bungalow
Carer: Home help

Initials: JS Sex: Female Age: 41
Disease: Multiple Sclerosis Length of time: 5 yrs
Previous occupation: Housewife
Ability: Limited hand movement. Uses manual wheelchair
Accomodation: Large ground floor room in private house
Carer: Live-in house keeper

Initials: BS   Sex: Male   Age: 65

Disease: Multiple Sclerosis   Length of time: 20 yrs

Previous occupation: Engineer

Ability: Hand movement on one side. Uses electric wheelchair

Accomodation: Adapted private bungalow

Carer: Wife at home all day

Initials: TP   Sex: Male   Age: 40

Disease: High spinal lesion   Length of time: 1 yr

Previous occupation: Chef

Ability: Only slight hand movement

Accomodation: Hospital, awaiting adaptation of flat

Carer: Wife and teenage children at home

Initials: PO   Sex: Male   Age: 49

Disease: High spinal lesion   Length of time: 5 yrs

Ability: No movement below neck. Uses suck/puff switch

Previous occupation: Blacksmith

Accomodation: Private room in residential hospital unit

Carer: Full nursing care

Provisional plans were made for three visits on approximately consecutive days. The plans for each of the days were as follows.

Visit 1. Initial setting up of the robot

Demonstration of robot

Skill learning by user (simple pick-up and place)

Demonstration of simple useful task

Visit 2. Skill learning by user

Simple useful task by user

Demonstration of more complex task

Visit 3. Useful task by user

Appraisal of tests.

The robot was only used with the demonstrator (the author) present. This was particularly for safety reasons, but also due to the setting up of the current system which needed to be done by an able bodied person.

The system installed on the dining room table of one of the volunteers is shown in Fig. 5.1

RESULTS FROM TRIALS.

Effectiveness

The users were introduced to the robot through simple pick up and move operations, progressing to more useful tasks which could potentially give them greater independence. Drinking was achieved using an ordinary mug, either using the "pour" facility, or using a straw, with the robot used to bring the mug to a convenient position.

User Input.

One of the most encouraging aspects of the user trials was the way in which subjects, some with no technical background, were able to quickly understand and master the control system. All were able to competently use the basic commands after only about an hour's experience.

It was found that with the current system it took a long time to do even simple tasks. To a certain extent the lack of speed was due to the user being unfamiliar with the controls, but even for an experienced user the speed of selection of a particular movement using a scanning menu is limited. The other major factor, however, is the speed of movement of the arm, which must be limited by the ability of the user to accurately and safely stop the arm. One major improvement in speed, and user effort required, is through greater use of preprogrammed routines.

Numerous small, but useful comments were made relating to the input. These included comments on the size and colour of the display, the speed of the cursor and the need to compensate for slight tremor. Initially red symbols were used on a blue cursor. Other alternatives tried were red on white and cyan on blue. It was suggested that an attempt might be made to indicate what colour switch should be pressed next by using appropriately coloured arrows. Thus red and blue arrows on a cyan cursor were used for a while. Eventually blue on a cyan cursor seemed most appropriate. The use of an audible "beep", when the cursor moved was useful and a switch with a definite "click" was also helpful.

The type of control system depends ultimately on the ability of the user. For the formal trials, as reported here, the one or two switch scanning system was used in all cases. However a joystick and roller ball have also been used as alternative input devices. For the slightly more able users (KW, JS, BS) an analogue input device, such as a joystick, would be more appropriate. For someone who can only manage a one or two switch system more emphasis could be put on preprogrammed routines. With respect to the suck/puff input used by PO, it was commented that it would be impossible to use such an input device while feeding.

Mechanical configuration

The system, intended to represent a simple workstation system, was simply a robot placed on a desk or table in the volunteer's home., rather than an integrated system. It was therefore seen by the users (in particular KW) as taking up an unacceptable amount of space for a private home. There was certainly insufficient space for the system in the small room which PO had in a residential hospital unit. A proper workstation must have the robot (and controlling computer/electronics hardware) better integrated into the whole system in order to use space more effectively. One problem, encountered with PO was that due to the size of his wheelchair, it was difficult to set up the robot. Any workstation system should accomodate a large wheelchair, with the user's legs perhaps horizontal in front of him.

A desktop workstation was chosen for this feasibility study since it was easiest to set up. It was noted that this approach might be less suitable for KW, JS and BS who were able to move around their homes in either electric or manual wheelchairs. They tended to use the mobility available and therefore it might be limiting, rather than liberating to be "tied" to a particular desk. A wheelchair mounted robot, for example, might be more appropriate. It is clear that the type of system must be appropriate to the ability and needs of the user.

Safety

Safety has always been considered important for robotic systems, and this is especially so when used by the disabled who cannot take avoiding action, and where the robot must by necessity operate in close proximity to the user.

Primary safety should ensure that the robot is not able to hit the disabled user. There are however situations where the object being held by the robot is required to come in contact with the user (for example feeding) and this must be allowed. The current system is sufficiently low powered and runs at such a low speed not to pose a serious safety hazard, but it is vital from the point of view of user confidence that the arm should not be able to hit the user. Thus limits should be put on its range of movement both using mechanical stops and software limits.

Secondary safety is probably more important. For a number of domestic tasks the robot is required to carry and pour hot liquids. Apart from any actual danger in the case of spillage, the disabled user is not able to take any remedial action such as wiping up the spillage. Spillage can occur if the gripper does not securely hold the vessel, allowing it to drop or tilt. The correct choice of suitably shaped vessels can limit this danger. Pouring operations should be carried out at a distance from the user, over a tray. The most critical situation involves drinking, when the hot liquid is being effectively poured ino the user's mouth. This must be under the very precise control of the user. In the trials the success of the drinking operation was most dependent on the correct seating position of the user relative to the robot. When this was correct it was possible to safely control the drinking operation.

Overall response of users.

JS: Since she is independently mobile in her wheelchair, is able to feed herself and is well looked after she would seem not to have a need for a robot. Specific dedicated aids might be of more use.

BS: He is in a similar situation to JS, though physically more disabled. Would have a use for numerous dedicated aids, operated through his environmental control system.

KW: Since he is mobile he would not have a use for a workstation as such, but a wheelchair mounted system might be of benefit. His greatest need is for the preparation of hot meals and drinks. this might be provided by a wheelchair based system or a fixed robot system in the kitchen.

TP: Since he has only recently had his accident, and his only experience of being disabled is in a hospital with full time care he was unable to determine what his needs would actually be. However he considered that a workstation based system might be useful when he returns home. He would not consider using the robot for personal tasks, such as feeding or shaving.

PO: He is content to have things, including feeding, done for him. The cubicle which is his home has insufficient space for a robot of any size. Apart from these considerations his situation would seem to benefit from a workstation system.

TASKS ATTEMPTED IN LABORATORY

Besides the trials described above, various tasks were attempted in the laboratory. Feeding may be a major task area for a robot (though note that some potential users would not want help in this area, as mentioned above). The only feeding task attempted with disabled users was drinking. The progression from this would be eating more solid food. (Feeding was not attempted with the volunteers in the trials partly because of the difficulties of arranging the preparation of the food, and since most of the testing took place in the morning or the afternoon when the volunteers did not want to feed.) Soup and yoghurt were satisfactorily consumed in the laboratory, using a specially bent (but otherwise standard) spoon, and using the specially written software routine. It took about 15 minutes to consume about 75% of the bowl of soup. During this period the soup remained satisfactorily warm. It was not possible to finish all the soup since the robot was not able to tip the bowl as an able bodied, two handed person would. It is considered relatively simple to progress from eating something which is semi-liquid, as soup, to something more solid (eg minced meat, mashed potatoes and peas).

Besides feeding, the preparation of food and drink has been considered. The robot was used to prepare a cup of coffee, using standard domestic equipment, including a standard kettle. The equipment was arranged around the user beforehand but there was no "hands on" intervention during the tests apart from turning on and off the kettle. The coffee was satisfactorily prepared, but took 30 minutes to carry out. Such a time is clearly unacceptable. The time could however be significantly reduced by the use of jigs, more suitable equipment (eg a hand held immersion heater, rather than a kettle), and preprogrammed routines. For the preparation of food, a microwave might be used, but this idea was not tested.

CONCLUSIONS

The robotic system and user trials have proved the potential of a relatively low cost robot manipulator to perform useful domestic tasks for the disabled. The task ability is currently restricted, mainly due to the limitations of a simple gripper. This may be solved both by the use of appropriate jigs and by a more sophisticated gripper.

Using only a very basic two-switch, or even one-switch, input it was possible to control a robot with five degrees of freedom. Such control is however slow. Whatever control ability is comfortably available from the disabled person should be used. The maximum use should be made of preprogrammed routines or part routines, especially for those with low control ability.

The system tested was workstation based. However, depending on the ability of the user it may be found that a wheelchair mounted robot, or a self-mobile robot would be more appropriate. We consider however that a workstation based system, in spite of its limitations, offers real potential at a relatively low cost and in a short timescale.

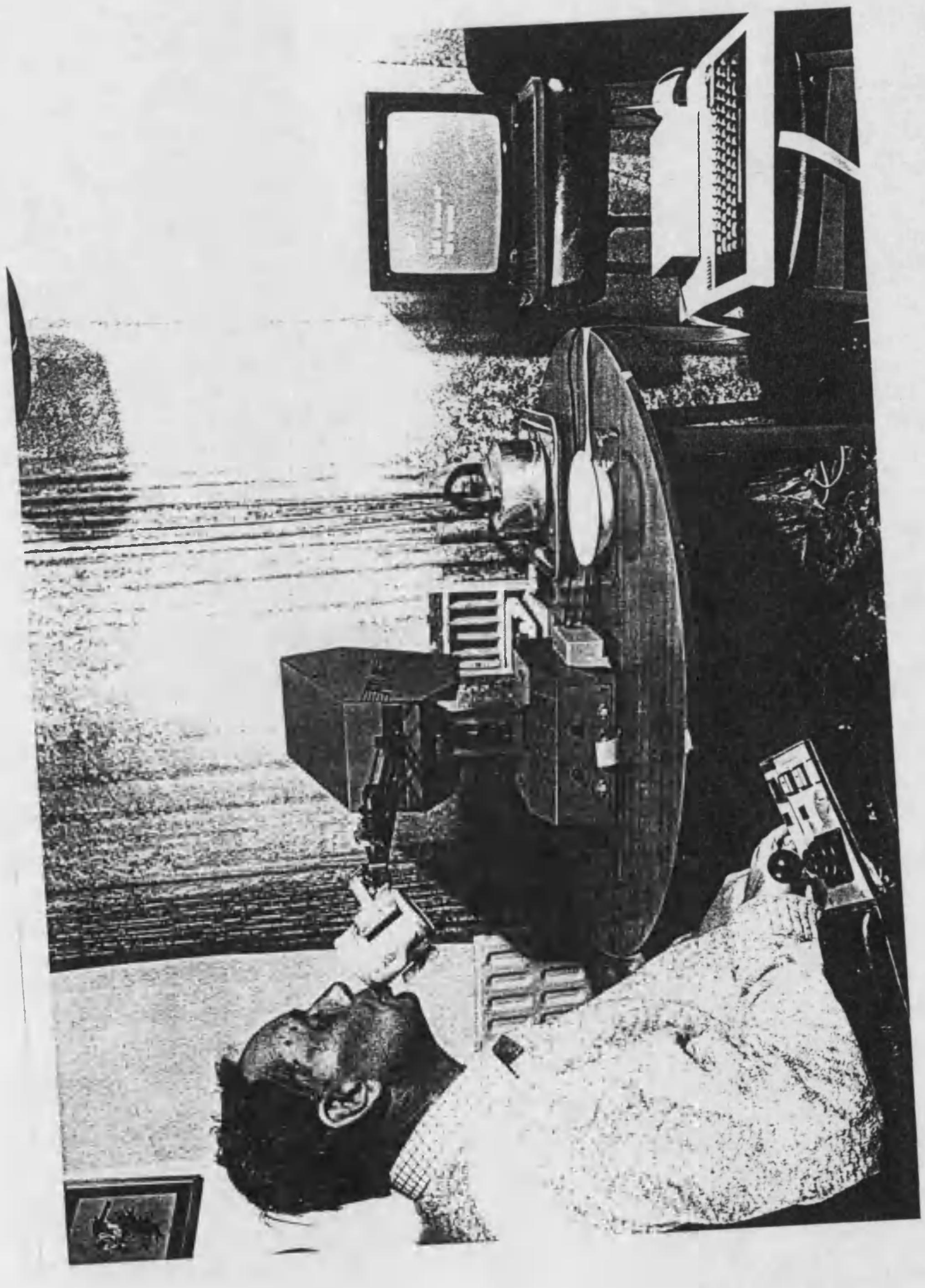


Fig. 5.1

Feasibility study trials.

Chapter 6. ATLAS WORKSTATION SYSTEM - TECHNICAL DESCRIPTION

INTRODUCTION

From experience with the feasibility study system a specification was drawn up for a workstation incorporating the Atlas robot. The Atlas robot was further modified in the area of the gripper. A new electronic control system was designed to facilitate control of the robot. Software was written in assembler for both the interface and robot control functions.

SPECIFICATION

The specification for this system was derived from experience and observations with the earlier system, feedback from users of the earlier system, and in discussion with the Occupational Therapy Staff at Odstock Hospital where it was intended to carry out preliminary trials.

Overall

It was decided to follow the workstation approach with a fixed arm, rather than a wheelchair mounted or freely mobile system. It was obvious from the earlier work that it was not feasible simply to place a robot arm on a desk or table top and expect it to carry out useful tasks. The arm needs to be integrated into a workstation.

Hardware

The Atlas arm would be used, integrated into a workstation. There should be room for a person in a wheelchair to sit at the workstation. A new electronic interface to the Atlas arm would be built, to improve the speed performance by taking the speed control of the motors away from the microcomputer onto a dedicated interface. An Acorn BBC computer would provide the main processor control. Because of the use of the system in a hospital environment the workstation should be movable, for storage and for wheeling onto the ward. The hardware, particularly the computer, should be securely fixed to the workstation for security.

Power supply

The complete system should plug into a single 13A mains socket with a RCCB protected plug.

Tasks

The following tasks were to be initially incorporated on the workstation.

- Cassette tape / radio
- Computer use. (A 5.25 disc drive should be used for compatibility with existing discs at Odstock)
- Mouth stick retrieval
- Book rack and rest

- 4 mains sockets and 4 low voltage switch sockets should be directly controlled for ancillary equipment.

The incorporation of feeding tasks was discussed with the OT staff, but they strongly felt that eating was a social task, and therefore inappropriate for inclusion on a workstation.

User Interface

The system should be usable without any intervention by an able bodied assistant. It should thus turn on with the touch of a single switch, and enter the robot control software. A 2 switch scanning menu interface system should be used. The robot should be controlled both directly (using a scanning symbolic menu) and by the replay of routines preprogrammed by the user. Besides use for controlling the robot the computer should also be usable for applications, such as wordprocessing. Use of the microcomputer would be by mouthstick, handstick or keyboard emulator.

MANIPULATOR HARDWARE

The manipulator used is again the Atlas robot. There are no modifications to the mechanical hardware, with the exception of a further modification to the gripper.

The gripper is closed by linear motion of a shaft, attached to the two jaws by a small roller chain. As the gripper motor rotates it rotates the drive shaft through spur gears. The drive shaft rotates in a threaded bush, thus giving the required linear motion. When the jaws close against an object the drive shaft can no longer move linearly, and so the threaded bush moves against a pair of compression springs. This arrangement gives variable force gripping, the force being proportional to the motor rotation after the jaws close against the object.

The limit of motor rotation is an optical limit switch on the motor output. Therefore the maximium force exerted at the limit position depends on the size of the object. This arrangement works satisfactorily for gripping a thin object. However for a large object, such as a mug, since the jaws close on the object after only a short linear movement of the shaft, a high force is developed before the motor limit switch trips. More specifically the problem is that the compression springs lock solid and the motor stalls.

The modification to overcome this problem (Fig. 6.1) involved putting a microswitch limit switch between the threaded bush and the fixed end of the compression spring. Another microswitch was fitted to determine the point at which the threaded bush started to move, and thus the point at which the jaws closed on the object. Though it was possible by this method to calculate the actual force applied by the jaws this was never implemented. Since the whole assembly moves when the arm extension operates, the microswitches had to be connected to the main body of the robot by a free cable. This was adequate but not tidy.

COMPUTER HARDWARE

The user interface and robot control software were both implemented on an Acorn BBC Model B Microcomputer. A twin double sided 40/80 track 5.25 inch disc drive was used. A colour or monochrome monitor was used as available. Display colours were chosen for good distinction with a monochrome monitor.

The Microcomputer was non standard in two respects.

a) An ATPL "Sidewise" Sideways ROM board with battery backed sideways RAM was fitted. The software was stored on an EPROM and data for user parameters and preprogrammed routines on the battery backed sideways RAM. This arrangement meant that the computer would enter the robot interface software on power up, and preprogrammed routines were available without needing to be loaded from disc.

b) The computer was housed in a Viglen case. This allowed the keyboard to be separate from the processor unit, attached by a flexible cable. This was used so that the keyboard could be readily positioned for easy use by a mouthstick or other input aid. The Viglen case also allows the disc drives to be mounted in the processor case. This was not used however, since it was required to mount the disc drives where they could be easily accessed by the robot for insertion of discs.

ELECTRONICS HARDWARE

Though the Atlas mechanical hardware was essentially unmodified, the electronics was greatly changed. Referring back to Fig. 4.4 it can be seen that the external microcomputer communicated to the multiplexer of the robot circuitry. Also referring back to chapter 4 it was stated that the speed of the motor was determined by interrupt driven software on the controlling micro. This was unsatisfactory firstly because of the demands on processor time of the external micro. Secondly only a limited ratio of speeds was available between different motors. Finally the speed value was specified by a variable value which was inversely proportional to the speed.

The new electronics hardware used here essentially replaces the interrupt driven software by solid state logic circuitry, and communicates directly with the motor drive boards. The hardware is illustrated in block diagram form in Fig. 6.2.

The Acorn BBC Microcomputer is interfaced via its 1 MHz bus to the robot control interface. The robot emulates a block of extended memory on the computer as listed in Table 6.1. For each motor the speed is written to a speed/control latch (Fig.6.3). Six bits from the latch are fed to the digital to frequency converter, which produces a train of pulses to the motor drive card. The pulses to the drive card also increment or decrement the motor counter, which may be read by the microcomputer. The remaining two bits in the latch are the motor direction and a motor on/off bit.

Motor control bytes	&FCE0 - &FCE5
Environmental control	&FCE6
Power control	&FCE7
Motor position counter	&FCE8 - &FCF3
Limit switch state	&FCF4 - &FCF5
Environmental input	&FCF6

Table 6.1 Extended memory allocation

The robot control interface board was constructed using a wire-wrapping technique. Due to the inadequacies of the hand tool used there were reliability problems, which resulted in a number of the joints needing to be soldered as the tests of the system proceeded. The 1 MHz bus cable (with an overall length of approximately 1.5 metres) needed to be screened since problems were encountered with picking up interference, particularly from the welding equipment in the workshop in the adjacent room.

The interface also allows the computer to read the state of the robot limit switches, to control the power supply to the robot and computer, to read switches set in the workstation environment and to control external devices. In order to provide a simple environmental control the computer has 8 bits to turn on and off external devices. Four of these bits control low voltage switches, and the other four turn on/off standard mains sockets.

The power control allows the computer to turn on or off the robot or computer. The computer is initially powered on by pressing either of the two input switches, which then turns on the bit in the computer to keep the computer power control on.

On the front of the workstation a 7 pin DIN socket (standard for equipment for the disabled) is provided for connecting a range of input devices, such as hand switches or a suck/puff switch. An infra-red link is provided so that a user may use a switch permanently mounted to his wheelchair without needing to make a "hard" connection.

WORKSTATION

The workstation was to be a "desk shaped" work area. The arrangement of the workstation must allow the correct spatial relationships of robot, user and tasks. There were two basic constraints. Firstly, since the Atlas arm has no yaw, the tasks must be arranged radially around the arm. Secondly, since the system is controlled by a human user, visibility is a vital consideration. There should also be as much room as possible for various tasks. In more detail the items to be located on the workstations are: The robot, the "task stations", the controlling microcomputer (or at least the monitor), and a general manipulation area.

The tasks initially incorporated were:

- Discs and disc drive (5.25")
- Car cassette player (auto reversing)
- Books and a reading rest
- Computer keyboard to be operated using a mouthstick
- Rack for holding the mouthstick

Various layouts might be considered as illustrated in Fig. 6.4. Of these arrangements (a) gave good visibility, but had a limited area for tasks and no position for the computer. Arrangement (b) was discounted because it also allowed only a limited area for tasks. Arrangement (c) was chosen, though it is obvious that visibility to some of the task areas is obstructed by the bulk of the robot.

In order to determine the more precise arrangement, the maximum and minimum reach of the arm should be considered. The maximum reach obviously puts a limit on how far away any "task" should be from the arm. The minimum reach is important when objects such as books or cassette tapes have to be removed from a rack or tape player. Another constraint was that, since the arm has a sliding extending arm, there must be clearance for the other end of the extending arm at the back of the robot.

The arrangement chosen is illustrated in plan in figure 6.5. In order to keep a reasonable depth it was necessary to modify the disc player by removing the power supply and shortening the case. (This is not considered an unnacceptable modification since disc drives are available without power supply units). The book rack which needs the least manipulative ability is in the position most obstructed by the arm.

Th workstation was constructed from 12mm plywood in a box construction, 125mm deep. It is constructed in two sections. One houses the robot, the tasks and most of the electronics, while the other houses the computer, and is made so that a wheelchair may be wheeled underneath the table top. The robot section is attached to a free standing supporting framework. The computer section bolts to the robot section and has supporting legs on the other side, with removable bracing at the rear. The whole workstation sits on 6 small castor wheels for mobility. The overall size of the workstation is 1.65m x

0.90m. The workstation is shown in the photograph in Fig. 6.6, and various points should be noted.

* There is ample space under the workstation for someone sitting in a bulky wheelchair.

* The robot arm is sunken into the work top to attempt to hide some of its bulk. (This did not affect the useful reach of the arm, rather it was an improvement since the arm could more easily reach table height with the gripper horizontal.)

* All the electronics are hidden within the depth of the workstation top. While proving a clean appearance this arrangement was unsatisfactory for the connection of different units. The problem was compounded since the electronics evolved, and was incoporated in a large number of boxes, rather than integrated as one unit from the beginning. The arrangement of the various electronics units within the workstation is shown in Fig. 6.7.

* A shelf is provided underneath the worktop. This was originally intended for possible housing of a computer printer, but this was never incorporated.

* 4 mains sockets are located on the back of the workstation for the mains appliances controlled by the system. There is a mains on/off switch and a single cable to a 13A plug with RCCB protection.

* On the front panel there is an emergency stop button which enables an attendant to cut power to the arm if required. The panel also has a socket for the control switch and infra-red receiver for the remote control switch.

* The system may be reconfigured from a "left hand" system (as illustrated in Fig. 6.5) to a "right hand" system (as illustrated in the photograph, Fig. 6.6). This is achieved by fixing what is the front of the "robot" section in Fig. 6.5 to the left hand side of the "computer" section, keeping the robot at the front centre of the workstation.

SOFTWARE

User features.

The features incorporated in the software, from a user's point of view, are illustrated in the menu tree structure in Figure 6.8. As in the previous system a scanning menu system is used and various interface options can be set up for different users.

Move. This is the main user interface, allowing the user to control the arm directly in space. Besides the single motor movements for base rotation, arm elevation and roll, and jaws open/close, there is also compound movement for vertical and horizontal motion. The algorithm for this motion is similar to that developed for the earlier system.

In order to improve fine user control of the motion a two speed motion is programmed. For the first short period (as defined for individual users) a slow speed of motion is used for fine movement, increasing to a faster speed for coarse motion.

Edit/create/replay When the arm is moved by the user the individual movements are saved in memory. The various commands which are used to define movements are shown in Table 6.2. Note that movements may be either absolute or relative. If it is required to save the operation as a routine for future use, the movements may be transferred to another section of memory (hence the option "Transfer") to be replayed, editted or saved for future replay.

Routines may be editted. The movement commands are displayed on the screen in shorthand format. The edit options available are to delete a line, merge several lines into one, change the speeds, and to change a movement from absolute to relative. A typical edit screen and routine listing is shown in Fig. 6.9.

Routines are saved in battery backed sideways RAM. A catalogue of directory and routine names addresses the individual routines. Six directories refer to six routines each. Thus there is space in the catalogue for up to 36 entries. Routine names may either be typed in from the keyboard, or default names are used. Routines are stored in order of creation. If a new routine is saved, it is stored at the next free address. If a routine is revised the original copy is deleted, and a new copy is created in the next free address. This method gives the best use of memory as there is no spare memory between adjacent routines. The addressing relationships used in routine storage are illustrated in Fig. 6.10.

One major feature incorporated in the replay of routines is the ability for the user to interact with the replay. Use of the "stop" switch allows the user to adjust the position of the arm. This is important if an object in the environment is not positioned precisely.

Home. This command sends the arm to its reset position, and then puts the wrist horizontal. Regular resets are important in a stepper motor system without any absolute position feedback, though individual motors are also reset when they come against the limit switches. The order of resetting the motors is chosen to make it least likely for the arm to hit objects in the environment, though if collisions are imminent, the stop switch is operative.

User switch options.

Various interface options can be set up for different users, relating to both menu operation and motor control. These are:

Switch options -

* Motor control. Either movement while the switch is held down, or to start on one command and stop on the other (suitable especially for suck/puff operation).
* Auto repeat on/off. Determines whether the the cursor scans while the switch is held down, or whether a fresh switch press is required to progress down each row
* Beep on/off. Turns on or off the "beep" facility for each movement of the cursor.

Speeds - Different speeds may be set for each motor. For those users who have less controllable switch actuation a slower speed will be required.

Delays -

* Latching delay. This is the period before the speed changes from the initial fine control speed to the higher coarse control speed.
* Anti tremor delay - a short delay to cut out unintentional actuation of the switch due to tremor or uncertainty.
* Auto repeat delay - delay before the cursor starts to scan if the switch is held down (auto repeat "on" selected)
* Auto repeat period - repeat period as the cursor scans down, while the switch is held (auto repeat "on" selected)

Motor Control Algorithms.

As described in the electronics hardware section, speed control is simply by writing a speed value to a memory location. Each 8 bit location requires a bit for motor on/off, a bit for motor direction and a 6 bit speed value. The speed value is directly proportional to the motor step rate. For direct control of a single motor of the arm by the user the control loop monitors the limit switches and checks flags set by an interrupt routine. The interrupt routine monitors the state of the user control switches, and returns a flag set to indicate "start"/"continue", "stop" (for pause) or "end" (to leave the motor control loop). When the motion starts a speed flag is set low, and after a delay period is set high. The state of this flag is also monitored by the main loop which sets the motor speed to an initial low value for fine control, then increasing to twice the speed for coarse motion after the initial delay period.

The arm may be controlled directly by the user in a straight line, either horizontally (radially) or vertically. The straight line algorithm is a development of that used in the earlier system. Due to the revised motor control electronics a better range of linearly variable motor speed ratios is available, giving better straight line control.

For replay of routines (ie movement of one or more motors to a set position) the control loop also monitors the number of steps for each motor to the target position. For the required motion the motor which has furthest to move (referred to as the major motor) is determined. This is set to the chosen replay speed value with a ramp down at the end of the motion to the required position. Other motors are set to speeds in proportion to the relative distance required to move. These speeds are constantly updated since, as only a limited range of integer speed value are available, the relative distances remaining will vary.

Methods of coding.

In order that the user might be totally independent in his use of the system it was considered important that the whole system should switch on into the robot software on the press of a single button. With the BBC Micro Computer there is no facility provided to enable this to be achieved easily, particularly since the computer has no battery backed RAM as standard. One method available however is to program the code as a "language ROM". Normally the computer will enter the BASIC language ROM on turn-on, but if another language ROM is in the highest priority socket, then this will be entered. The complication however is that the code must then be written in assembler.

With the standard BBC Micro, four sideways ROM sockets are available, though two of these contain the BASIC ROM and the Disc Filing System ROM. In order to provide more room for sideways ROMs, an ATPL Sideways Rom board was fitted, allowing up to fifteen ROMs to be fitted, and also providing a battery backed sideways RAM. The sideways RAM was used to store movement procedures programmed by the user, and user parameters. Also this area was used for program development.

The use of ROM/RAM may be summarised as follows.

Development:

Normal RAM	Storage of routines, User parameters, Variables.
Sideways RAM	Program code.
EPROM	Look-up table, Text.

Final system:

Normal RAM	Variables
Sideways RAM	Storage of routines, User parameters
EPROM	Program code
EPROM	Look-up table, Text

A memory map for the final system is provided in Fig 6.11.

This arrangement of separating the text and look-up table on one ROM and the program code on another proved unsatisfactory since it was regularly found that a change in one ROM rerquired changes in the other. A solution planned was to separate the User Interface software (and text) onto one ROM, and the Robot Control software (and look-up table) onto the other. The Interface software would then access the Robot Control software using "spare" operating system calls, which are provided for this purpose. This method was never implemented, but a similar arrangement of separating the Interface and Control software was used in the subsequent (Wolfson) system.

Assembly method used

When programming in assembler on the BBC a problem occurs when programming large programs. Since the assembler program must occupy memory space (and is less compact than the final machine code) it is not possible to assemble the whole program in one operation. Since variables will be common to different parts of the program, and entry points for routines must be known a method must be used to transfer these values. These values are set up in BASIC procedures which are appended to each of the assembler files as required.

* Blocks of variables. These blocks relate to different functional areas of the program, such as utilities, motor control, movement routines and general global variables.
* Local variables are used for each assembler file.
* Addresses for data and constants.
* Start addresses of routines. These are split into utilities, and other subroutines.
* Each assembler file has entry points at the start, using the JMP statement. Thus even if the details of the assembler file are changed, the entry points for the routines are fixed.

Details of the assembler files used are given in Table 6.3.

Movement Commands used in Replay routines

Code	Name	No of param's	Parameters	Description
01	MOVETO	14	code steps speed	Move to absolute position
02	MOTOR	5	code motor steps speed	Motor to absolute position
03	MOVE	14	code steps speed	Move relative
04	PAUSE	3	code time	Pause
05	ADJUST	1	code	Adjust position directly
06	HOME	1	code	Move to home position

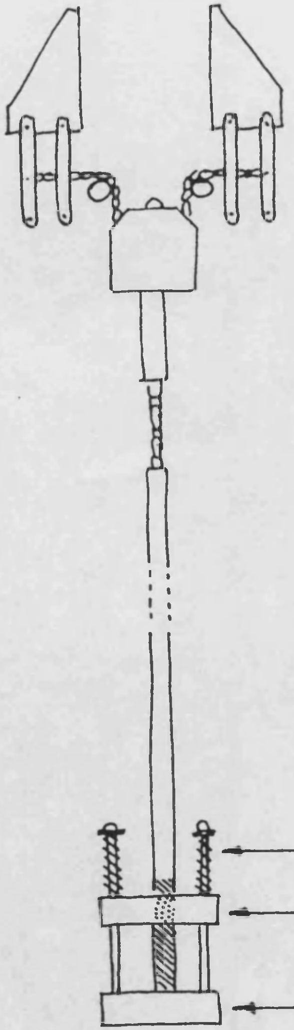
Table 6.2

Assembler files (as arranged in memory).

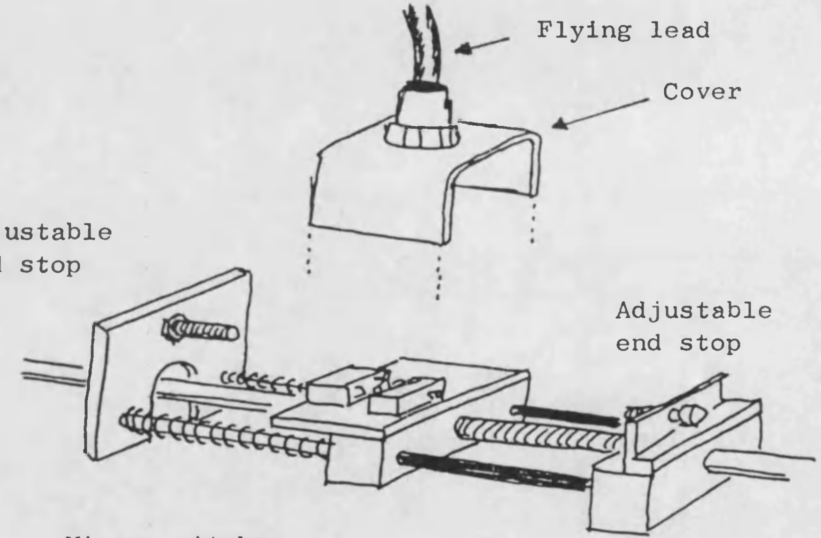
HEADER (&88 bytes)	Identifies the ROM as a language ROM, and provides entry points to run the program.
MAIN (&2C3 bytes)	Contains the main user interface menu structures.
MOVMENU (&1C2 bytes)	The menu for direct control of the arm by the user.
MOTOR (&6D6 bytes)	Motor control loops and associated motor control routines.
INTER (&511 bytes)	Interpolation routines provide conversion between cartesian position and motor positions. (Uses a 2D look up table).
ECU (&1F8 bytes)	Environmental control menu.
EDIT (&237 bytes)	Allows user to edit routines.
ROUTLS (&70C bytes)	Load/save routines.
ROUTMOV (&61E bytes)	Replay routines.
EDITOPT (&3D3 bytes)	Edit options for use when editting routines.
SWITCH (&287 bytes)	User switch control interrupt routines.
UTILLOC (&4F0 bytes)	Utility routines specific to this application. Includes low level routines to access the motors and other features of the interface.
UTILGEN (&5AC bytes)	General utility routines, mainly arithmetic and screen display routines.
UTILED (&16D bytes)	Utility routine specific to the editting functions of the program
ERROR (&D1 bytes)	Error handling routine reports errors to user.

Table 6.3

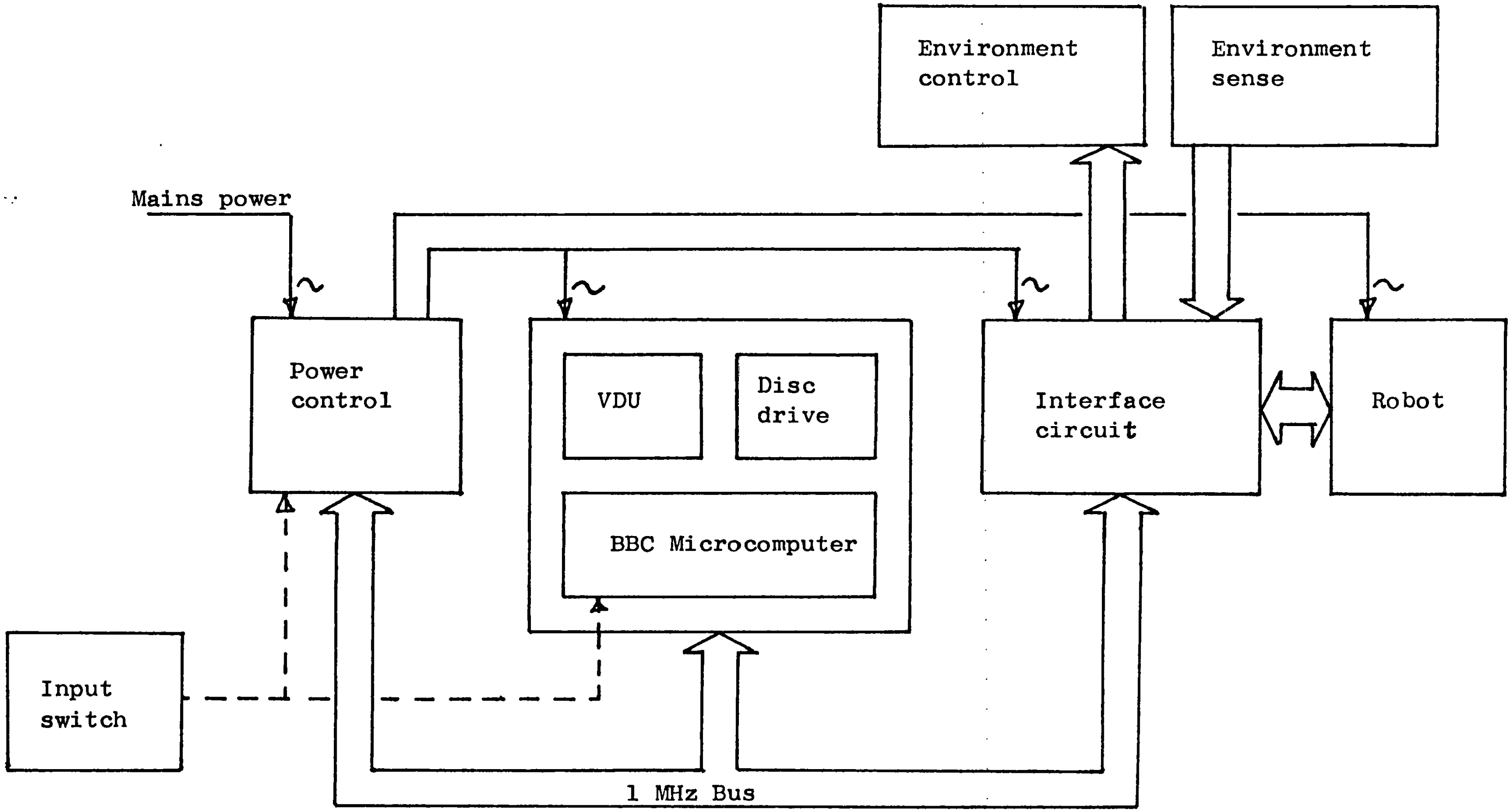
Fig. 6.1 Modifications to gripper



Basic gripper arrangement

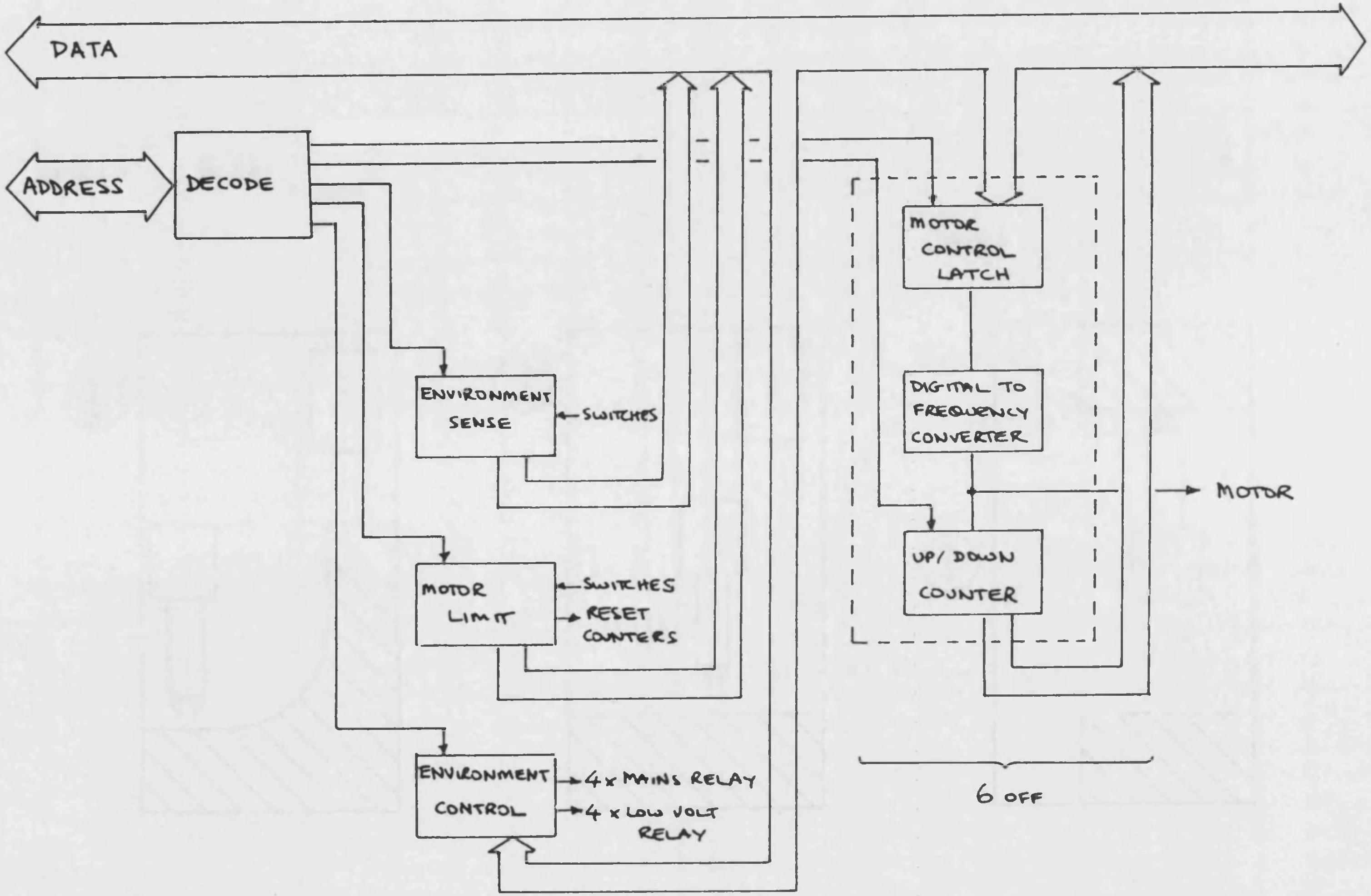


Modification to detect and limit maximum grip force



Overall block diagram of electronics (Atlas workstation)

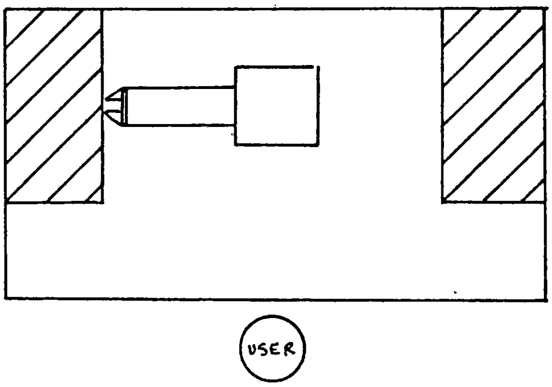
Fig. 6.2



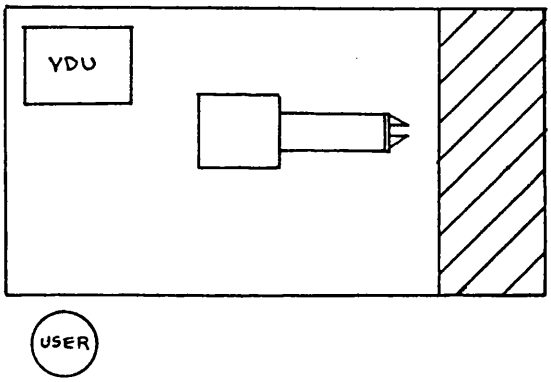
Motor control interface (Atlas Workstation)

Fig. 6.3

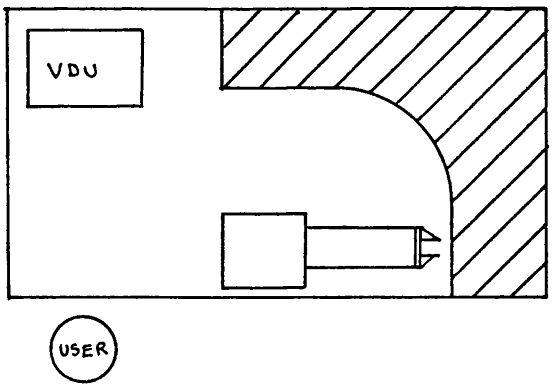
(a)



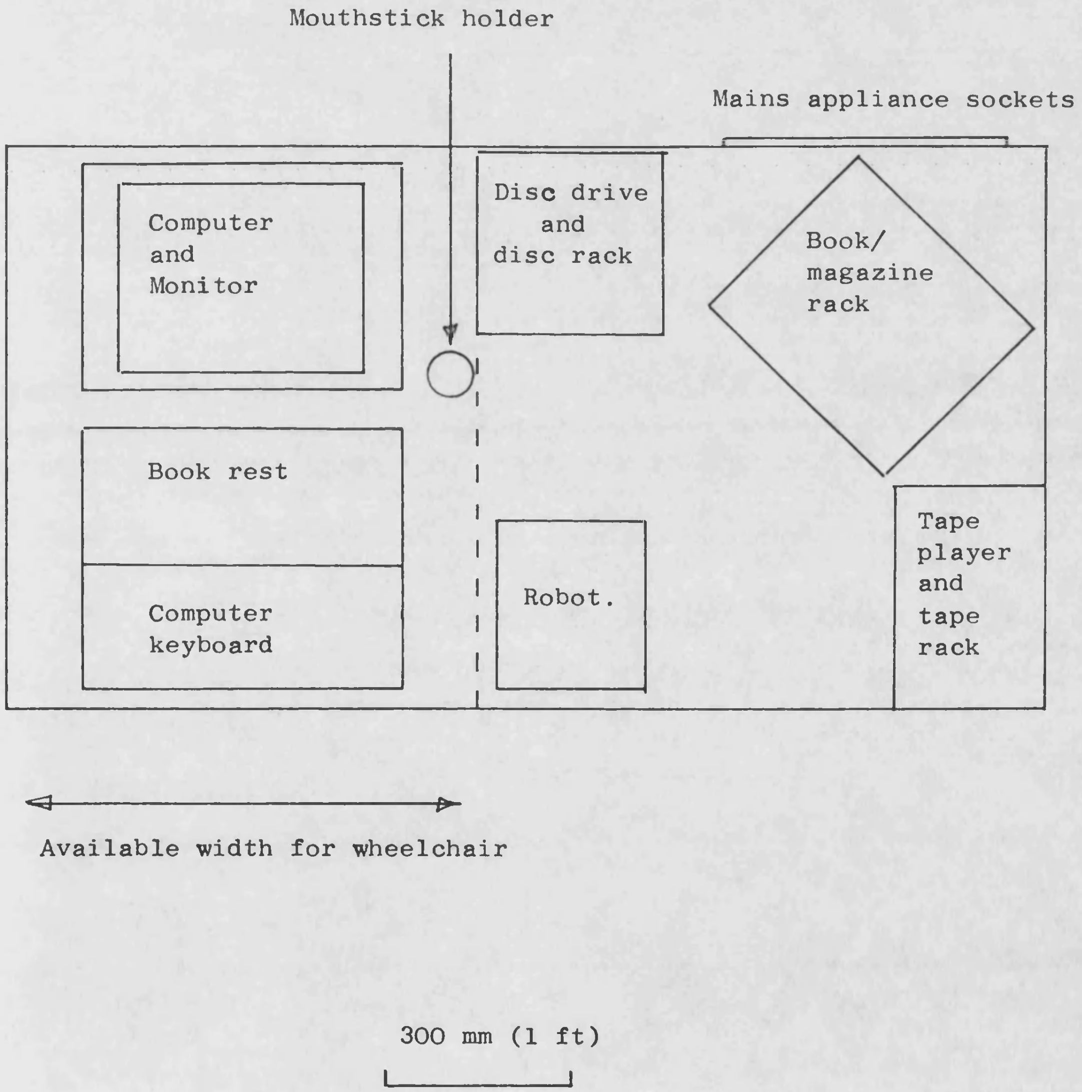
(b)



(c)



Potential arrangements of workstation Fig. 6.4



Final arrangement of Atlas Workstation Fig. 6.5

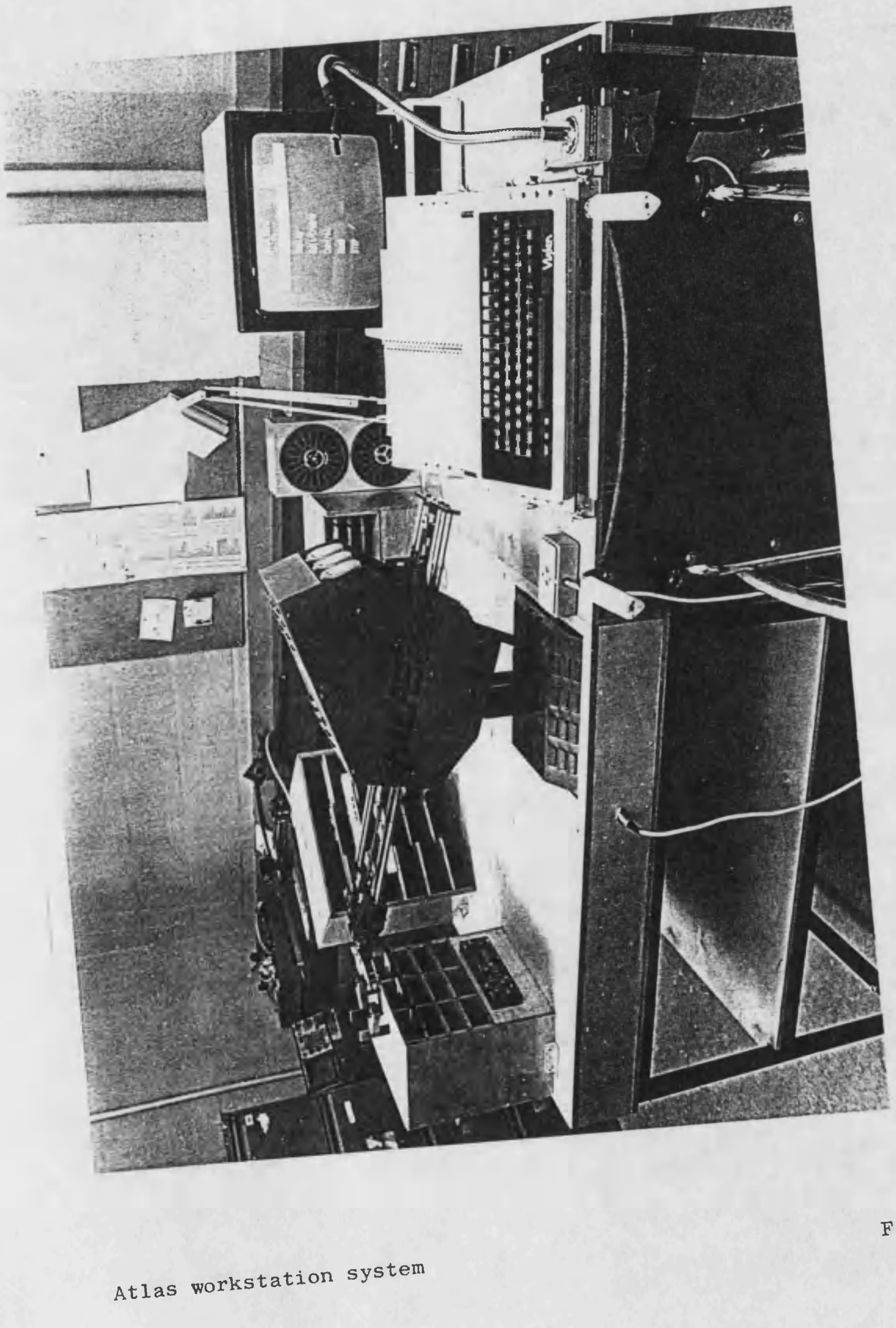


Fig. 6.6

Atlas workstation system

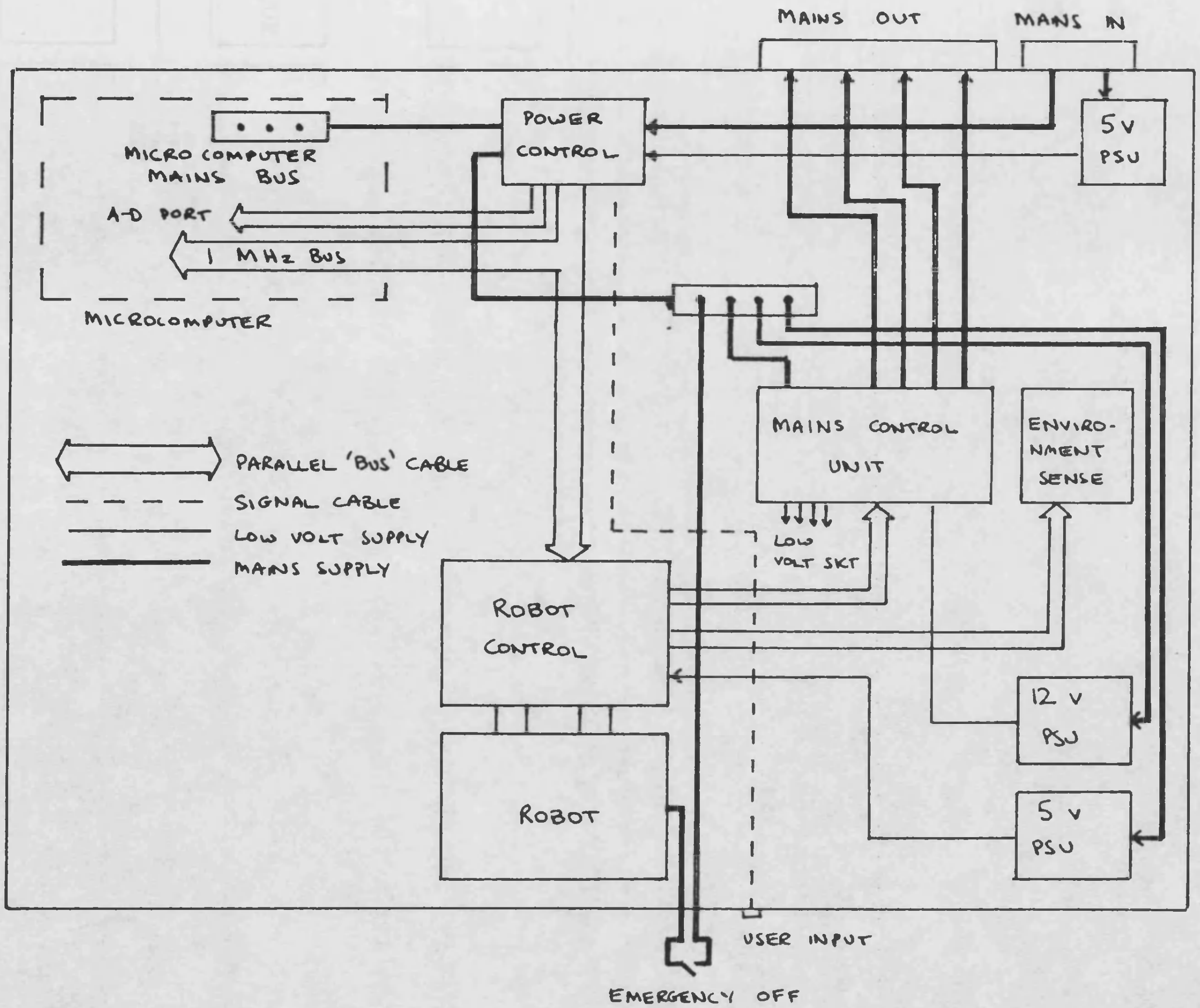
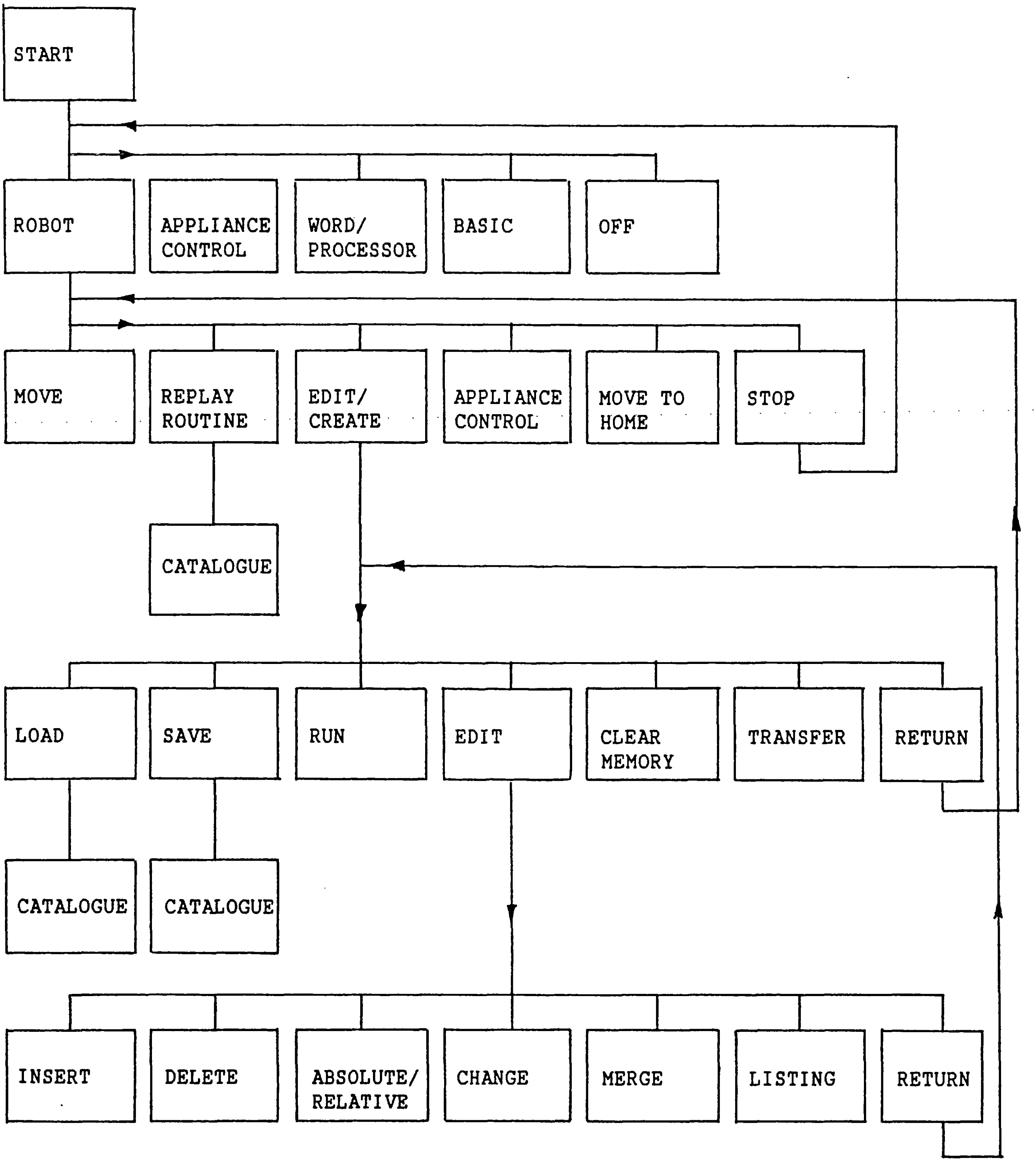


Fig. 6.7

Arrangement of electronics within Atlas workstation

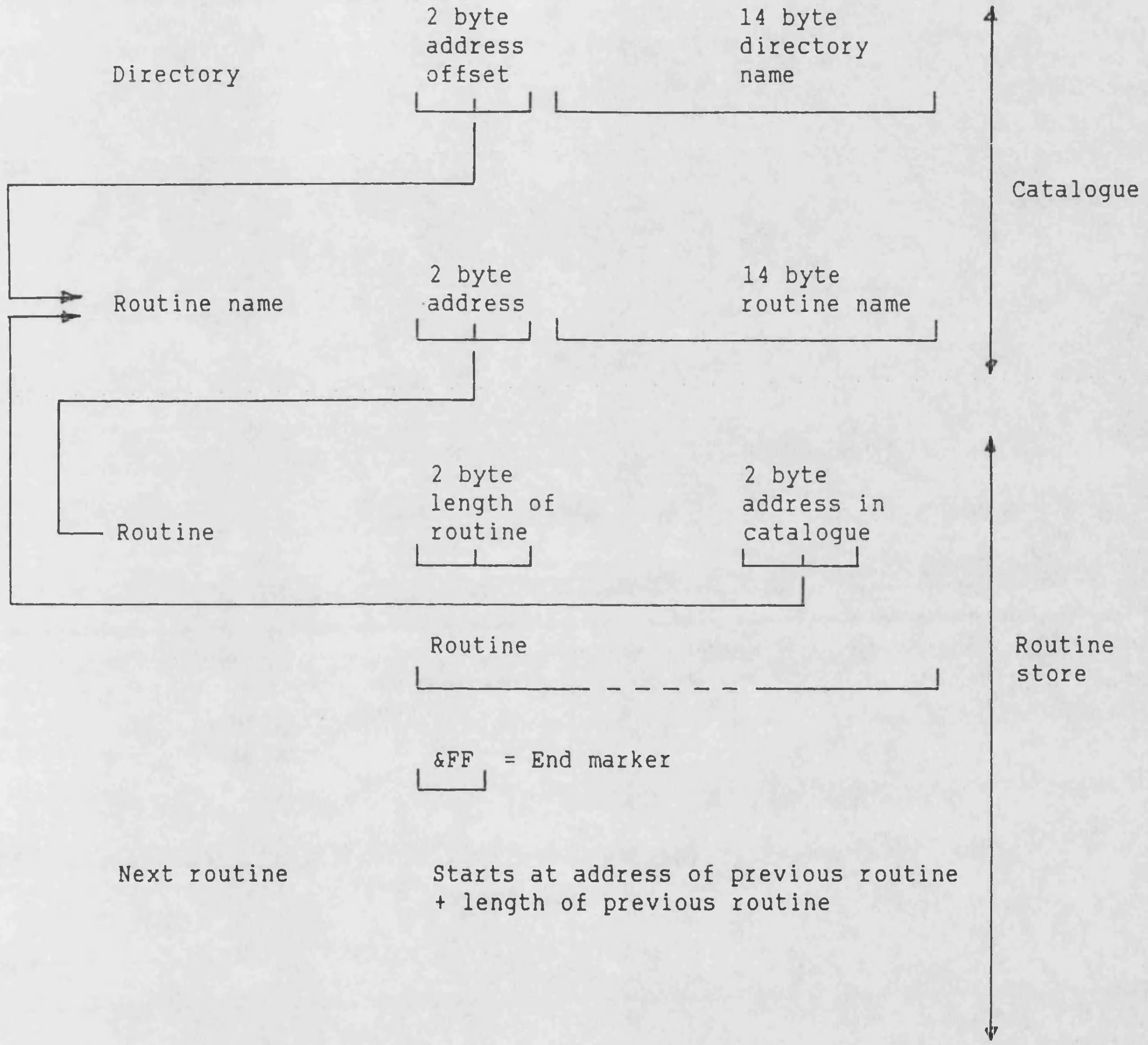


Overall menu tree structure
(Atlas Workstation)

Fig. 6.8

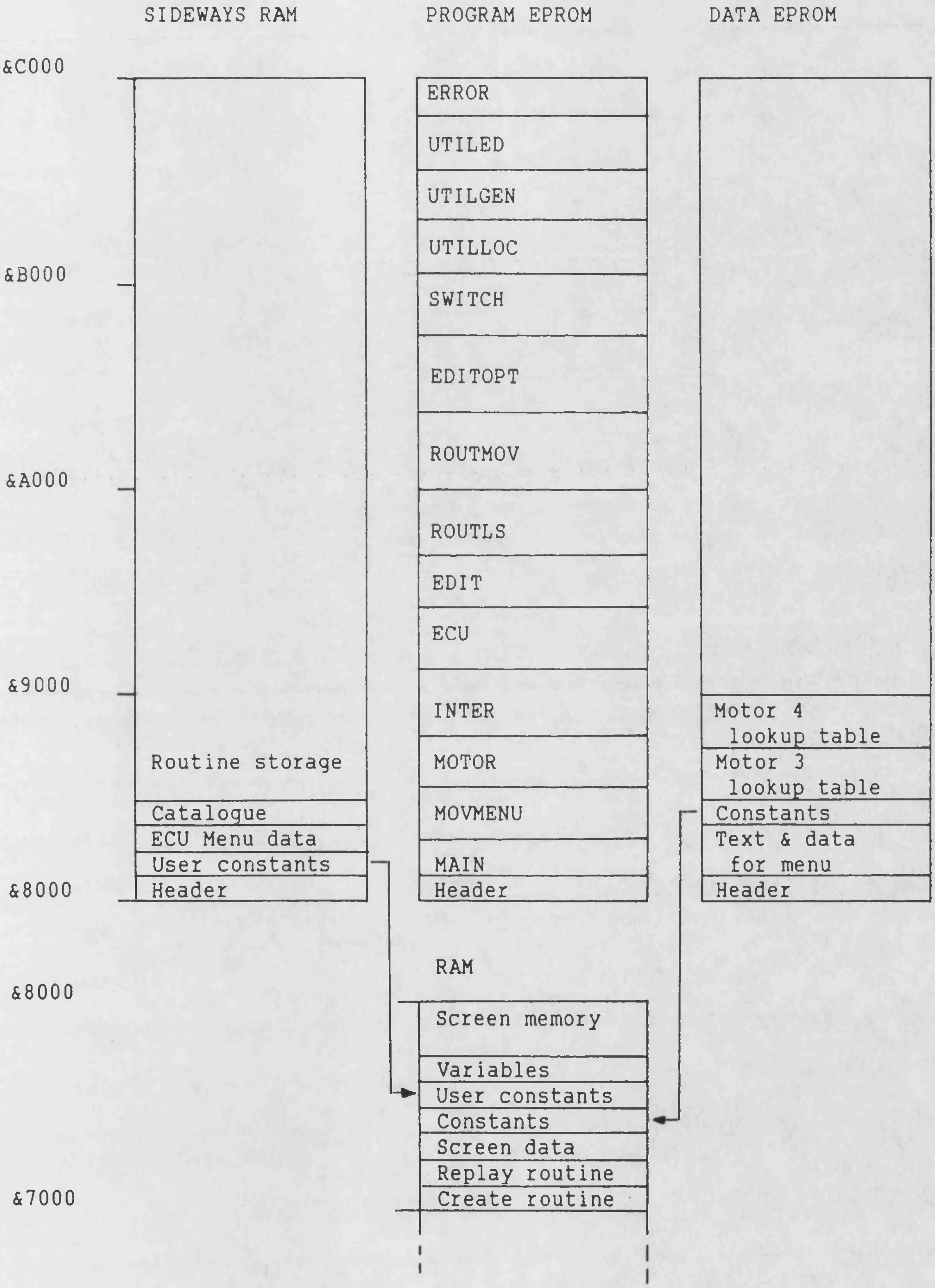
```
EDIT ROUTINE - EXAMPLE

001  MOVETO()          EDIT OPTION
002  MOTOR(5)          A.  INSERT
003  MOTOR(2)          B.  DELETE
004  MOVE()            C.  ABS/REL
005  PAUSE(10)         D.  CHANGE
006  MOVETO()          E.  MERGE
007  MOVE()            F.  LISTING
008  MOVE()                RETURN

                       jaws    :4361
                       thetaR  :90
                       thetaE  :20
                       x       :9.7
                       y       :2.3
                       thetaB  :270
                       speed   :2
```

Edit screen (Atlas Workstation) Fig. 6.9



Addressing relationships used
in storage of routines

Fig. 6.10



Memory Map (Atlas Workstation) Fig. 6.11

Chapter 7. ATLAS WORKSTATION SYSTEM - USER TRIALS

INTRODUCTION

The system was tested at the Duke of Cornwall Spinal Injuries Unit at Odstock Hospital, Salisbury, UK for trials with various patients suffering from high level spinal injuries. Preliminary trials took place in September 1988 with two users, and the main trials took place over the period February to June 1989.

The preliminary trials were valuable as a preparation for the main trials. They allowed modifications to be made to the hardware and software for more effective trials later. Six volunteers took part in the main trials

Each of the volunteers who used the robot had one or two sessions with the robot, and was able to become familiar with the basic system and the way in which it could be used. As well as recording the volunteers' subjective comments and reactions to the system, a questionnaire was administered in order to collate and formalise the responses.

GENERAL REACTIONS

Six volunteers took part in the main trials (Table 7.1). This was not intended to be a statistically relevant group, but did cover a wide spectrum of backgrounds. Male and female were represented, an age range of 23 years to 53, with computer experience ranging from extensive to nil. All had had their injuries within the past year.

The reactions of the users to the use of a robot, and suggestions of tasks which might be implemented are laid out below for each of the six users, in order of age.

Subject A. Male .. Aged 23 .. Single

This user had two sessions with the robot. He controlled the robot using a suck/puff switch. During the first session he was introduced to the control of the robot, was able to familiarise himself with the basic move commands and carried out the simple exercise of picking up a tape box. He got confused over which of the suck/puff switch commands to use for a particular movement. During the second session he inserted a tape into a tape player with the assistance of a preprogrammed routine. The only other task suggested was to turn a TV on or off.

He found that visibility of the tasks was poor. This was particularly difficult for this user, who had limited neck movement. He also felt that the size of the desk was too large. His father queried the cost effectiveness of the system.

Subject B. Male .. Aged 35 .. Married

This user was very interested in the robot, having worked with computers. He had two sessions with the robot, and a third was planned but had to be cancelled due to the computer failing. It was not possible to rearrange the session as he was about to leave the Unit. He used a suck/puff switch. In the first session he was introduced to the use of the robot. He quickly picked up the method of control and was keen to try out difficult tasks to discover the system's limitations. In particular he experimented with picking up, and replacing in its holder, a mouthstick, and also inserted and removed a cassette from the tape player. During the second session the methods of creating a preprogrammed routine were demonstrated. It was intended for him to create a routine of his own, but this could not take place due to the reasons mentioned above.

Subject C. Male .. Aged 39 .. Married

This user had one session with the robot (during which the system was not functioning correctly). He used a two switch microswitch. The loading of a tape was demonstrated, and he carried out the exercise of picking up a tape box with the robot. His interests in using the robot were oriented towards workshop applications, such as assisting in the operation of a lathe. He suggested the possibility of using a robot on an overhead gantry or mounted on the wall.

Subject D. Male .. Aged 50 .. Married.

This user had one session with the robot. He used a two switch microswitch. It was felt that a lower profile version of the switch would have been preferable. He was interested in the use of a more conventional "mouse" as the input device. The basic operation of the robot was demonstrated, and then used to put a tape in the player. He easily picked up the basic method of operation and carried out the exercise to pick up a tape box. Because of his interest in, and familiarity with computers, the insertion of a disc into the drive was demonstrated.

Subject E. Female .. Aged 52 .. Married.

This user had two sessions with the robot. In the first session the basic control method was demonstrated. She used the robot to pick up the mouthstick, and then the loading of a cassette into the tape player was demonstrated. In this first session she used a suck/puff switch, but would have preferred a single switch. This was set up for the second session, and found to be an improvement for her. The reason for the improvement was partly because she found the suck/puff switch obtrusive, and also because with only one input switch there was not the uncertainty of which switch was required to be selected. She thought that visibility was poor on the system. She queried whether she would want to use the radio/cassette player in the context of what was meant to be a vocational workstation. Although she was a computer user she could not see what use the system would be to her.

Subject F. Male .. Aged 53 .. Married.

This user had one session with the robot. He used a two switch microswitch, but found it uncomfortable to use. The system was explained and demonstrated, and the subject used the robot to pick up a tape box. He found the system difficult to use and didn't come to any familiarity with the control method. He felt that it took up a lot of space and was expensive for just a few jobs, especially as he had no interest in using a computer.

SPECIFIC POINTS RAISED

1. The whole system should turn on with a single switch.

2. The means should be provided to operate the microcomputer. This may be through an emulator. If by a mechanical means (eg mouthstick) then the robot may need to swing the keyboard into an appropriate position and provide a mouthstick or handstick.

3. Insertion of discs. The preferable disc size is 3.5" rather than 5.25" as used in these tests. (This size was used to be consistent with the 5.25" discs used elsewhere in the OT department). The robot should be able to reach a disc drive built into an IBM compatible PC, mounted either horizontally or vertically. (This is more adaptable than the current arrangement where the drive is mounted separately). Alternatively a hard disc might be used, cost around £400 for the BBC Micro and widely available on IBM compatibles.

4. Printer options. Requests were made for the robot to be able to operate a computer printer.

Paper in: Fanfold paper, sheet paper or envelopes.

Paper out: Tear off fanfold, or remove sheet paper or envelopes.

5. Books must be taken off the rack and placed either on a reading rest, a page turner or for the page to be turned by the robot. Whatever method is used it is vital that there is a

way of turning the pages and not just of moving books onto a bookrest.

6. Entertainment is incorporated in the workstation in the form of a cassette player, and other possibilities include the use of a CD player or video cassette player. It may be that a dedicated device might be more appropriate for these tasks since such devices would naturally stand in a corner of the room for relaxed viewing/listening by the whole family. Devices may be commercially available, perhaps operated by an infra red control.

7. Feeding. There was a generally negative reaction as to whether feeding was an appropriate task for the robot. Certainly there are good reasons why eating would not take place in a "workstation environment" except for light refreshment such as a hot or cold drink.

RESULTS OF QUESTIONNAIRE

The questions asked are given in the appropriate tables. For some of the questions one or other of the subjects did not respond, for various reasons. This was particularly true for subject F, who showed little interest in the system.

Rating of various aspects of the system (Table 7.2).

	Good	Satisfactory	Poor
Noise	ACD	BF	E
Speed	E	BCD	AF
Layout of workstation		A	BCDE
Visibility		A	BCDEF
Visual appearance		A	BCEF
Ease of use	BCE	AD	F
Potential usefulness		BCD	AEF

Table 7.2. How do you rate the following aspects of the system?

Reaction to the noise of the robot was varied. This was probably due as much to the users expectations of how noisy a robot should be rather than the actual noise level. Ideally a certain level of noise is beneficial when the arm is moving from a safety point of view.

There are conflicting requirements concerning the speed of the robot. If it is too slow then the user will be frustrated over the time it takes for the arm to move from one position to another. On the other hand if it is too fast it will be difficult to control accurately. The control system should allow fast coarse movements and slow fine movements. Faster movement should be used for replay of routines.

Three questions related to the overall layout and size of the workstation, visibility from the users point of view, and the visual appearance of the system. These aspects were rated poorly. This was not unexpected and is ultimately due to the geometry of the Atlas arm used. Ideally an attractive layout of the workstation should be determined, good visibility from the user to the tasks arranged, and the robot geometry chosen to allow this, rather than starting from an inappropriate geometry.

The response to the "ease of use" relates to the scanning menu system. It can be seen that the replies covered the whole range, though the consensus was that it was relatively easy to use. It was observed that nearly all of the users were relatively competent with the system at the end of their short trials. Since it is difficult to separate appreciation of the interface system from the input device used, further comments are made below, with comments on the input devices.

The final question relating to potential usefulness got a poor response. This will be discussed later.

Input device (Table 7.3)

	Used in tests	Considered appropriate	Preferred
Suck/puff	ABE	ABCE	AB
Double switch	CDF	CDF	
Single switch	E	ACEF	CE
Handstick		BF	
Chin joystick		B	
Mouse		D	D
Voice		E	

Table 7.3. What input devices would you consider appropriate for controlling the robot system?

The users were asked to comment on the input devices which had been used, and suggest other possible devices. The input devices available for use in these trials were a two switch hand operated microswitch, a two switch suck/puff device and a single hand operated microswitch. Some users found the single switch scanning system easier to use than the double switch system. This was due to the fact that with a single switch system one has to be concerned with just the timing of the switch press, and not the choice of which switch. For users using the hand operated microswitch there was also the physical difficulty of moving from one switch to the other.

The users were also asked to suggest which other devices they considered appropriate for the control of a robot. Of the devices mentioned a handstick, mouse or chin joystick could give input more compatible with normal computer use. Alternatively a joystick could be used to give direct analogue control of the arm movement. Voice input was mentioned by one user, but by another as being inappropriate. Voice control may be appropriate for high level control (eg "Load disc") but not for low level direct control. Ultimately the input device chosen would depend on the physical ability of the user.

Users were asked whether they would want a system which used direct control of the robot, or simply the replay of preprogrammed routines. All replied that they would require the replay of routines, and four said that they would also require direct control of the arm.

Evaluation of Tasks

The users were asked whether the tasks set up on the workstation were of use to them. (Table 7.4.). Since the users had different backgrounds, needs and expectations the responses varied. The environmental control facility of the workstation was rated well (though this does not involve the robotic aspect of the system). Use of the tape player did not rate highly, reflecting possibly the fact that the system was seen as being of most use in a vocational setting. Manipulation of discs and books was generally useful. Provision of a mouthstick to the user was not considered useful for this group of users.

	Essential	Useful	No Use
Environmental control	AE	BCDF	
Tape		BCDE	AF
Disc	E	ABCD	F
Books	D	AC	BE
Mouthstick			BCDEF

Table 7.4. Do you consider the tasks incorporated on the system to be of use to you?

The users were then asked what general task areas they saw as being important for a robotic system (Table 7.5.). Of importance was work, communication and hobbies. Communication can be interpreted mainly as activities associated with wordprocessing and possibly also use of a telephone. Hobbies is an area which has not been investigated to date. One of the users was interested in the use of a robotic system for woodworking and another for lathe operation. Cooking was another application seen more as a hobby, than as a necessity. Entertainment (eg watching television, listening to a tape) was rated poorly because it was seen as a social activity, rather than one associated with a desk set in the corner of the room. The personal applications of feeding and personal hygiene were rated poorly, the use of a human assistant being preferred.

	Important	Not Sure	Unimportant
Work	BCDE		A
Communication	CE	AB	D
Hobbies	CE	D	AB
Entertainment	B	AC	DE
Feeding		C	ABDE
Personal hygiene		C	ABDE

Table 7.5. Which of the following task areas do you consider most important for a workstation system to be able to cope with?

Final response. (Table 7.6.)

The users were asked whether they would use such a system if it were provided to them. The majority replied that they would use it, and only one considered he would never use it. Finally the users were asked whether they would consider buying a system. Half of the users said they would consider buying such a system. Only one was prepared to state a price, and quoted £1000. This is a lot less than such a system could be provided for.

	Regularly	Occasionally	Never
Would you use such a system if it were provided to you?	BCD	AE	F
		Yes	No
Would you consider buying such a system?	BCD	AEF	

Table 7.6. Potential use and market of a robot workstation system.

Other rehabilitation applications of robotics.

Being familiar with a workstation system, the users were asked about their reactions to a freely mobile robot arm, and a wheelchair mounted robot arm. They were shown photographs of projects which have investigated these aspects [7,37].

When asked about a freely mobile robot arm there was scepticism about whether the technology was available to provide such a device, and uncertainty about how it would be controlled. It was felt that if there was a carer living at home (most of the users expected to be in this situation when they left hospital) then the system would not be much use. However three said they would use it regularly and two might consider buying one.

A wheelchair mounted robot was felt to be useful, but with some definite reservations. Users would not want to feel hemmed in by gadgets and controls and the arm should be easily demountable from the wheelchair. Interestingly a much wider range of tasks was mentioned as being appropriate to a wheelchair mounted robot. These included eating and drinking, toiletting, reading and opening doors. Two of the users would use such a device regularly and would consider buying such a system.

DISCUSSION OF TRIALS.

The original intention was that after an introduction to the robot system by myself, the users would then use the system regularly, under the guidance of Occupational Therapy staff, developing their expertise and suggesting and implementing new tasks. In practice most of the users only used the robot system once, under the direction of myself (this involved 11 visits to Salisbury). This allowed them to become familiar with the basic way in which the robot could be controlled, but not to develop any further tasks. The reasons for this are as follows:

1. The emphasis of the department is very much on the rehabilitation of patients for return to their own homes and possible employment. Therefore, while patients are introduced to the use of a computer for vocational rehabilitation, the prototype robot system was not seen as being immediately relevant to their present needs. The patients were, to a greater or lesser extent, still coming to terms with their accidents. Most were hopeful that they would regain at least some of their ability. They were not sure what their situation would be when they returned home. In future trials a greater emphasis should be on tests in people's own homes. However, all tests of such a device with potential disabled users are valuable at all stages of development and produce information and insights which could never be obtained through tests with non-disabled subjects.

2. The robot was introduced (by nature of the tasks set up on it) as being for use by a computer user. Therefore those patients who had no desire to use a computer did not see the robot as being of any use to them. They therefore had no further interest in the robot system.

3. The OT's were stretched in carrying out their own work, and as the robot was seen as an extra, they were not able to become involved in using it with the patients. For them to have become familiar with using the robot a certain amount of time would be necessary for familiarisation with the system. The robot was seen as an external project with which they were helping, rather than one for which they had any direct responsibility.

4. There were reliability problems with the system. One problem area was the computer which occasionally crashed. The other problems were connected with the BIME designed control electronics and were due to the intermittent failure of the wire wrap connections.

CONCLUSIONS

The overall reaction to the system was favourable, but two main problem areas were identified. The first related to the specific workstation layout tested. This was considered to be too large, with poor visibility of the working area and inappropriate appearance for a domestic environment. Since the workstation layout was determined by the geometry of the Atlas arm, changes will necessitate either the use of another commercially available arm or the design of our own arm for an integrated workstation.

The second, and more fundamental problem area was the usefulness of the system. One of the main benefits of a robotic system is its flexibility to carry out varying tasks. It had been hoped that in these tests the users would suggest tasks which they wanted the robot to carry out. In a hospital environment however the users were not able to visualise the problems of living independently and ways in which a robot might assist them. User's reactions to the robot system were also affected by the way in which it was presented. In this case it was presented as being primarily a system for vocational use of a computer, and this possibly limited the other uses which they could visualise.

Details of users.

Patient identifier	Age	Sex	Marital status	Lesion level
A	23	M	S	C5
B	35	M	M	C6
C	39	M	M	C5 (incomplete)
D	50	M	M	Central cord C3 (incomplete)
E	52	F	M	C6
F	53	M	M	C4/5

Previous employment.	Computer experience
A - Clerical	None
B - Builder, Computers	Installation & repair
C - Engineering Inspector	None
D - Finance Director, Developer, Farmer	Extensive
E - School bursar	Accounts, wordprocessing
F - Plasterer	None

Table 7.1.

Chapter 8. WOLFSON WORKSTATION SYSTEM - OVERALL DESIGN

INTRODUCTION

The specification for the Wolfson workstation system was derived from experience and observations with the Atlas workstation system. In particular a more appropriate workstation arrangement was obtained by the use of a purpose designed arm with a suitable geometry. Various workstation layouts and robot geometries were considered.

SPECIFICATION

The specification for this system was derived from experience and observations with the Atlas workstation system. Feedback from users came both from anecdotal comments and the replies to the questionnaire. Many features are common to the earlier system.

Working envelope.

The Atlas based robot workstation is 3' deep, by 5'6 wide. This is considered too large for a domestic environment. Based on the size of a reasonable sized desk, a realistic target size would be 2'6 by 4'6. Within this area would need to be located the following items of equipment:

Computer + Keyboard	18" wide	x 2'6 deep
Disk drive	12"	x 9"
Book storage	12"	x 9"
Tape/Radio	9"	x 7"

In addition other tasks may be added, particularly feeding. The robot will therefore need to operate in a working envelope defined by these dimensions. The robot should interact appropriately with the tasks. Much of this will be a function of the gripper, but the overall arm configuration will need to comfortably reach all the tasks.

An associated constraint is that of visibility. The user should have an unobstructed view of all the tasks.

The aesthetics of the robot should be appropriate for a domestic environment. This will put a constraint on the height allowed for the robot, which should probably be no more than 2' above the level of the workstation top.

The workstation trolley is to be a self contained unit and therefore the robot should be permanently attached to the workstation structure.

Safety

Mechanical stops (as well as software checks) may be used to restrict mobility of the robot near the human user. In some directions low force may be appropriate.

Under emergency "power off" conditions the robot should either not move, or return to a safe stable position in a gentle manner. The gripper will remain in its position holding whatever may be in its grasp.

Noise

The current system is too noisy. The noise level should be acceptable for a domestic environment.

User Interface

The user interface should again be a scanning system, similar to that used earlier. It should again be initially based around the BBC Microcomputer, though other computers may be considered later. The interface microcomputer should be independent of the processor used for robot control.

Gripper (See Chapter 10 for specification)

Numerical specification

Resolution: 0.5mm, with repeatability to within 1mm
Speed: Max speed defined by approx 5 seconds to move from one extreme to other for each motor. Min speed: .01 ms-1
Load - 1 kg at full reach.
Power Supply - Domestic Mains through a single 13A socket (including environmental control). RCCB protection should be incorporated.

ARM GEOMETRY

One of the weaknesses of the Atlas based system was the overall layout, which suffered from poor visibility and excessive size. The geometry of the Atlas robot was in a large part responsible for this. Being able to design our own arm allowed us to use a geometry which was most appropriate for a workstation environment.

Various workstation arrangements (without at this stage specifying manipulator geometry) were suggested. These are illustrated in Figure 8.1. All are initially based around a rectangular desk.

The major shortcoming of the Atlas robot was the lack of yaw. This dictated that all the tasks needed to be radially arranged, leading to a poor use of space. Any robot geometry considered should therefore have yaw freedom. The Atlas needed its pitch freedom to keep the gripper at a constant elevation, as the elevation of the arm varied. Constant elevation of the gripper is necessary and this will invariably be in a horizontal (or possibly vertical) position. Constant gripper elevation may be obtained either by the use of variable pitch at the wrist or through the use of a geometry which keeps the elevation constant.

There are numerous robot geometries which may be considered. The major ones are sketched in figure 8.2, and evaluated below.

Cartesian: The axes of the arm are such that the arm moves in a rectilinear framework. This is an ideal arrangement for a rectangular desk top working envelope. However it is not so easy to implement this arrangement. All the actuators for the three major movements are linear, with significant stroke. In an industrial setting the "X" and "Y" actuators would be carried on a framework above the work are, but this is not acceptable from an aesthetic point of view. Alternatively tracks at desk top level could be used, but this would severely compromise the use of desk top space for manipulation and placing of objects.

Cylindrical: In this arrangement base rotation is coupled with vertical elevation and horizontal extension. Because of the base rotation, wrist yaw would be needed to allow the wrist to be oriented as required. The use of a sliding horizontal joint is not ideal for a workstation due to the need to provide clearance at the "rear" of the robot for the sliding member, though a more complex telescopic arrangement could be used.

Spherical robot: This is basically the Atlas arrangement. Wrist yaw would be required. The problems associated with a sliding horizontal joint have also been noted.

Articulated robot: This very common arrangement has rotational joints at all three major axes. It has a good working envelope having both a good reach and being able to work close to itself. Yaw would be required because of the base rotation. One disadvantage is that the second and third joints have to act against gravity at all times. This leads to high power consumption unless the joints are made non-backdrivable. Also relatively high powered actuators will be required.

SCARA (Selective Compliance Assembly Robot Arm): This arrangement has "shoulder" and "elbow" rotation in a horizontal plane and vertical actuation of the end effector. Yaw would be required for orienting the gripper. This arrangement is ideal for pick and place assembly operation, with the gripper pointing down. However the incorporation of vertical actuation at the wrist leads to a bulky wrist.

Jointed cylindrical (Modified SCARA): This places the vertical actuation at the base, with "shoulder" and "elbow" rotations. This overcomes the objection to the SCARA configuration. Wrist yaw would be required, but pitch may not be necessary.

The jointed cylindrical geometry seemed most appropriate. Pitch freedom would not be incorporated initially. The vertical actuator, working against gravity, would be hidden below the desk top, while the rotary actuators may be smaller, not needing to work against gravity.

WORKSTATION LAYOUT

From the workstation layouts considered, and the use of a jointed cylindrical arm, two arrangements were chosen for further evaluation. One with task modules arranged at the back of the workstation and the arm in the front corner. The other with the tasks at the side, and the arm at centre back of the desk. (Fig. 8.3). These two arrangements and the Atlas arrangement were made into scale models (Fig. 8.4), approximately 1" to the foot, for discussions with staff and patients at Odstock hospital.

Many of those interviewed had seen or used the Atlas system and were familiar with its shortcomings. The general feeling was in favour of scheme "a" with the tasks at the back. This was considered a more attractive arrangement. Many with high spinal lesions will have poor neck movement and would need the tasks to be ahead rather than to the side. The placing of the robot to the side, at the front of the desk, had a good psychological feel, acting in a similar sense to the user's own arm. One person interviewed suggested the idea of placing the desk in front of a window, and being able to look out ahead. Such an arrangement would not be possible with scheme "a".

From the interviews with the models and the choice of jointed cylindrical arm made above, the overall design chosen was based on Fig. 8.3 a.

DETAILS OF WORKSTATION

The workstation was initially built to the size quoted in the specificaton, 4'6" by 2'6". The under desk space was made 31" high to clear a wheelchair, of width 32" and with no obstructions underneath all the way to the back. The major components are the worktop, the cabinet housing the vertical actuator and the electronics, the side frame, the task cabinet and the user interface computer. The completed workstation is illustrated in Fig. 8.5.

Details of the construction of the workstation are shown in Fig. 8.6.

Work top: This is a single sheet of oak veneer faced chipboard, with a small cut out to clear the vertical actuator post which on assembly is filled with an in-fill piece.

Cabinet: Constructed from a framework of 1" "Speed Frame" with panels of oak veneered chipboard. Doors open at the front to access the vertical actuator, and at the side to access the electronics. The electronics is mounted in a 19" rack, above the power supply unit and the power control unit. Mains sockets are fitted on the back for the environmental control and the user interface microcomputer. There is a mains on/off switch for the whole system at the back, and also outlets for control signal leads to the user microcomputer and user input switch socket. The user input switch socket is mounted on the front of the cabinet. The emergency on/off switch is mounted on the front of the cabinet

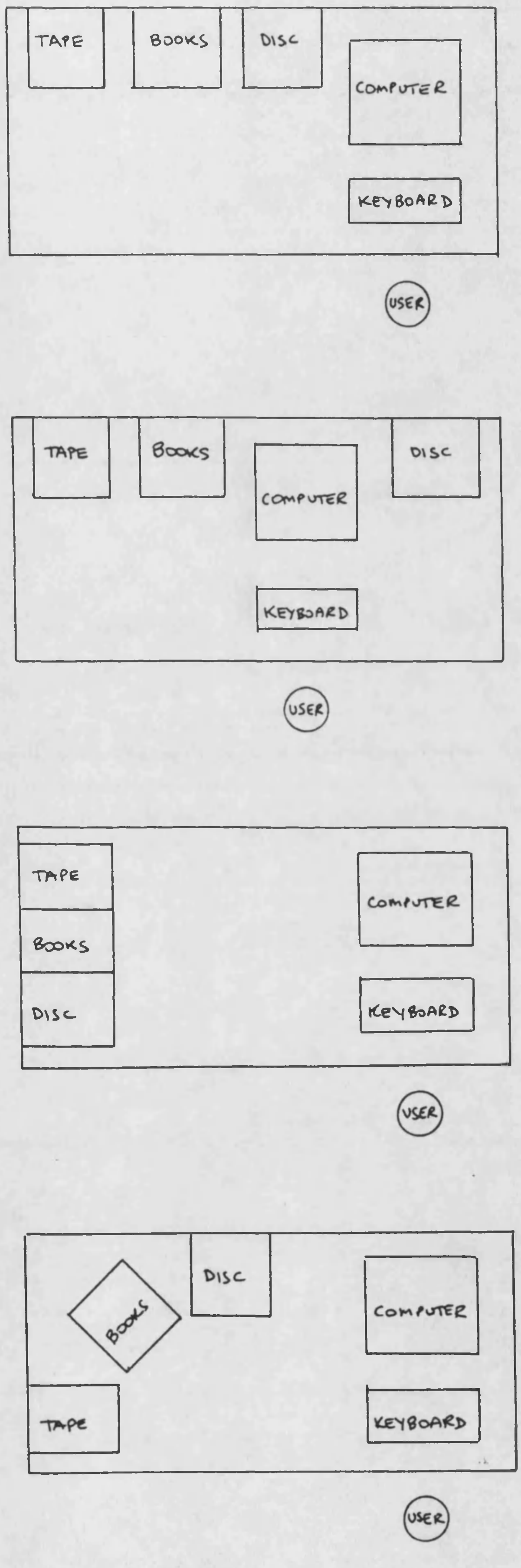
Side frame: The side frame is constructed from 1" "Speed Frame", with an oak veneered side panel. The frame bolts to the cabinet, with a strengthening bar at the rear.

Task cabinet: A cabinet was constructed to hold all the various tasks which in the first instance might be used with the robot. These were a book shelf, disk drive and disk rack, and car cassette player and cassette rack. Subsequently the single task cabinet was replaced by individually placeable units for the cassette player and book or magazine storage.

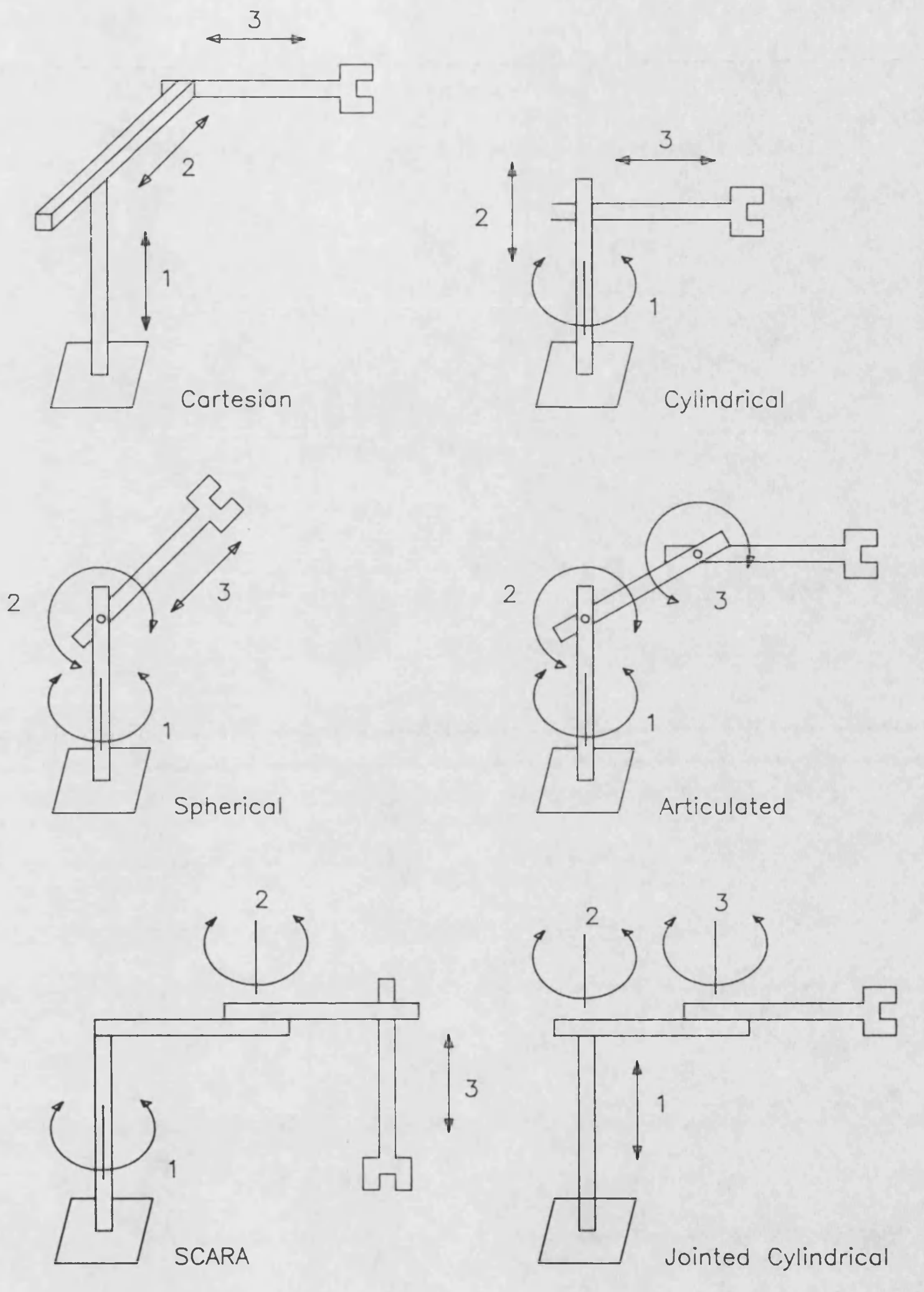
EVALUATION OF WORKSTATION

The whole workstation dismantled easily and could be easily transported in a small "car sized" (Astramax) van. It would be easier to handle if the work top was split into two, but the one piece top was aesthetically better.

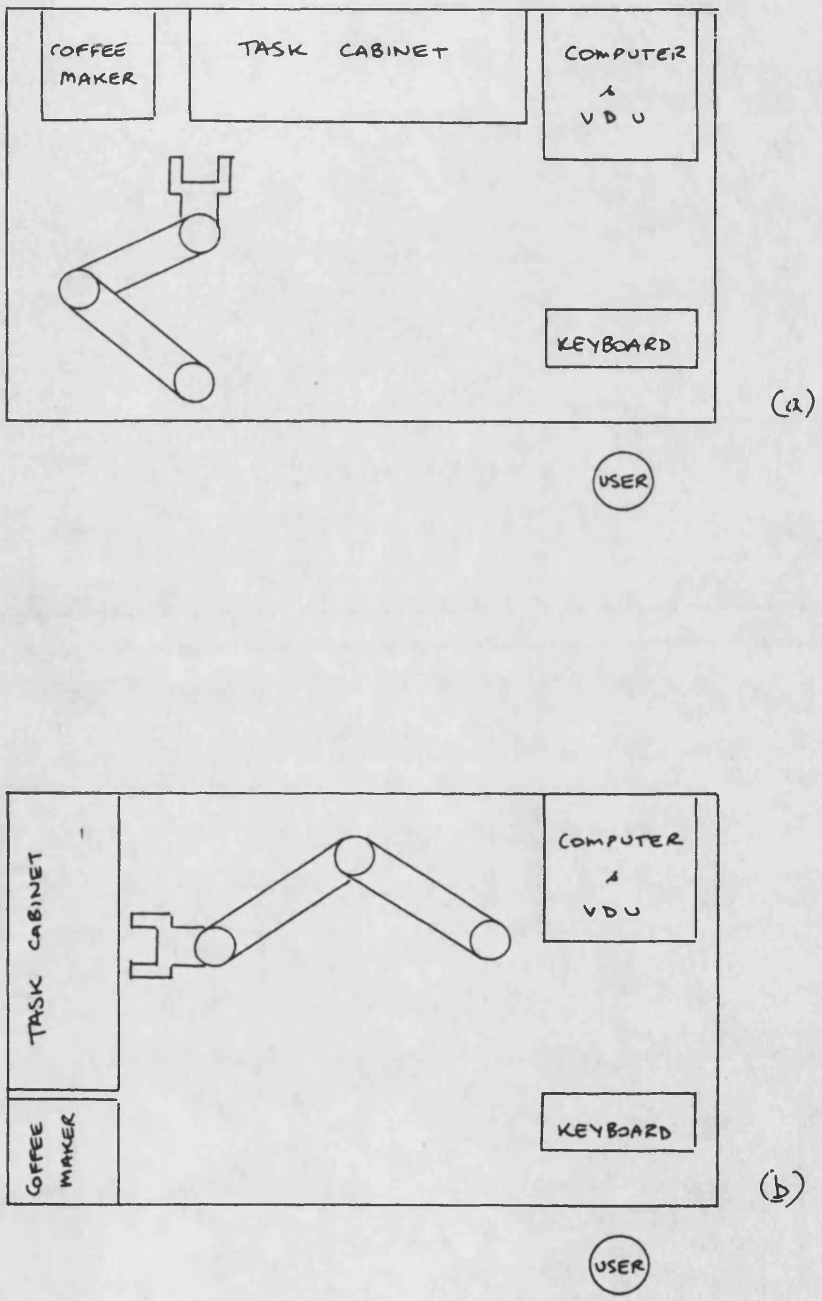
When initially tested it was found that due to the depth of the task cabinet, and the difficulty of manoeuvering the arm near its own base the work envelope was not as effective as initially thought. For this reason the worktop was extended to a depth of 3'. Although over the specification size, the arm was much easier to manoeuvre.



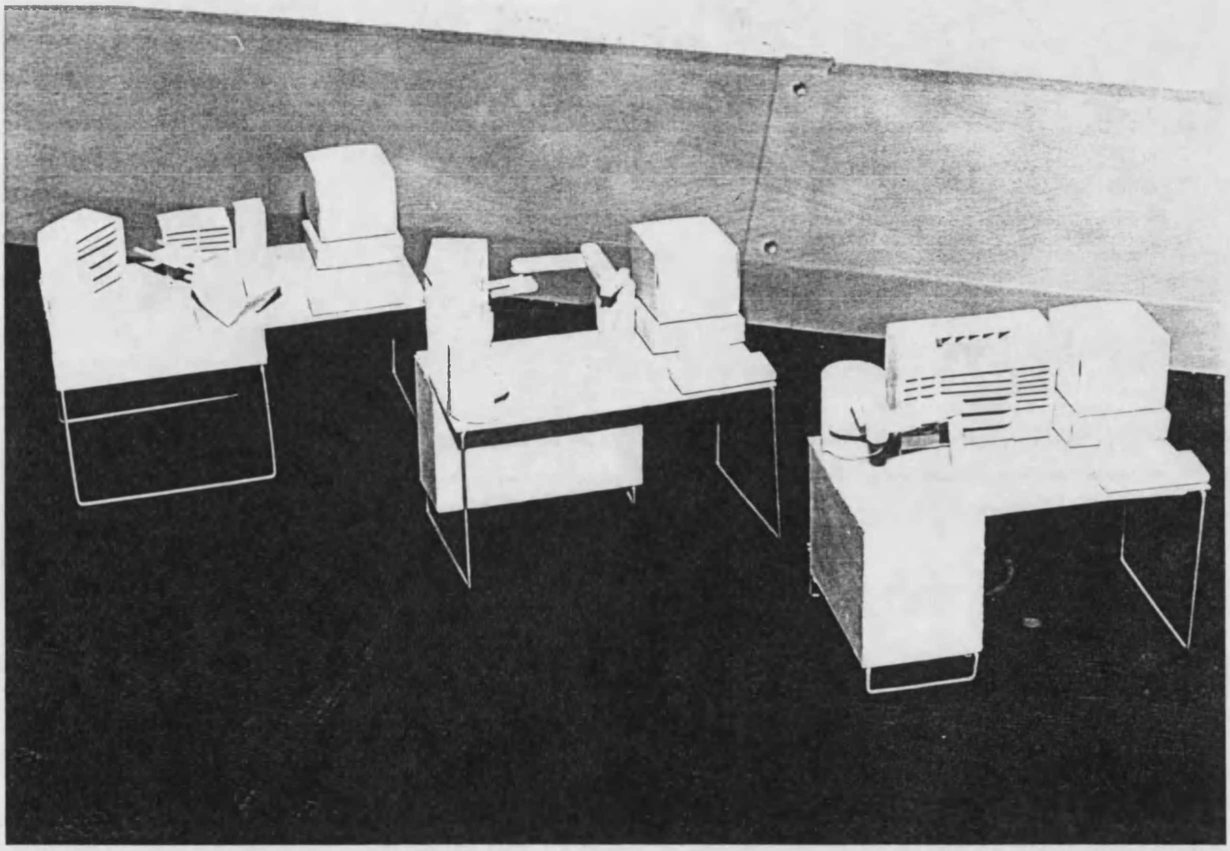
Possible robot workstation layouts. Fig. 8.1



Example robot geometries. Fig. 8.2

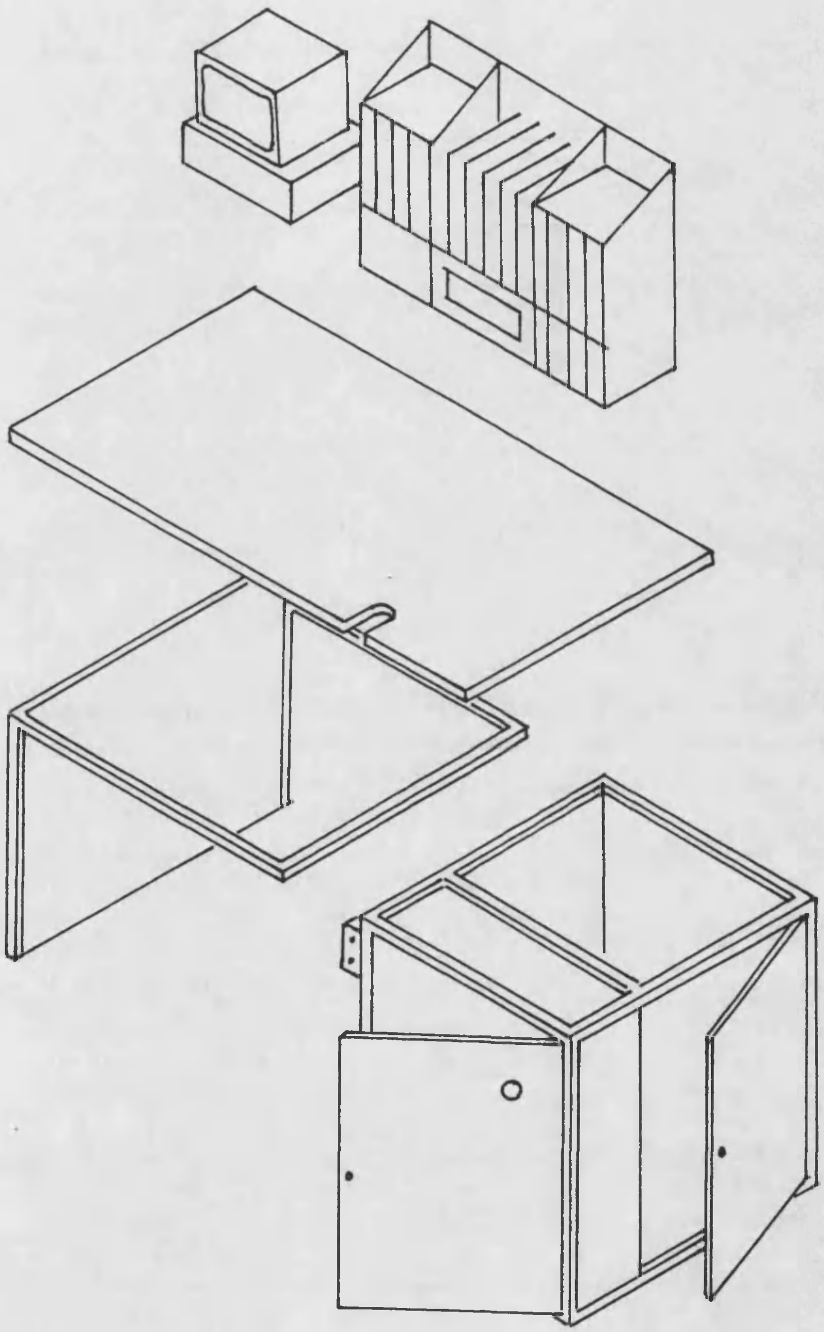


Shortlisted robot workstation arrangements Fig. 8.3



Models of workstation arrangements. Fig. 8.4

Completed workstation and manipulator Fig. 8.5



Construction of workstation Fig. 8.6

Chapter 9. WOLFSON WORKSTATION SYSTEM - MECHANICAL HARDWARE.

INTRODUCTION.

With the jointed cylindrical geometry the design can be split into two parts, namely the main arm and the vertical actuator.

The upper arm is constructed from standard aluminium extrusions. Rotary actuation is provided by dc motors/gearhead units, driving through a bevel gear stage and toothed belt. These rotary actuators are mounted within the arm structure. Two trial joints were constructed before the design was finalised.

The vertical actuator is an open structure with a dc servo motor driving a toothed belt. The weight of the arm is balanced by a constant tension spring. A trial joint was first constructed.

OVERALL PRINCIPLES.

With the jointed cylindrical geometry chosen as described in the previous chapter, the design can be split into two parts. The vertical actuator is below the desk top, hidden from view. The main arm is above the desk top and needs to have an aesthetically pleasing appearance.

The arm may need initially to be constructed in relatively low quantities as cheaply as possible. For this reason the use of plastic mouldings, metal castings or custom extrusions was discounted. Instead the use of standard aluminium extrusions was chosen. The cross section of the arm is therefore constructed from 1" x 2" U channel, and 3" plate. This is illustrated in Fig. 9.1. The overall section has a high bending stiffness, though high shear forces must be transmitted between the plate and channel. From an aesthetic point of view, the sides are clean, but the upper and lower surfaces are covered with screw heads for assembly of the section and fitting of components within. The aluminium surface may be polished or anodised. Machined end pieces are used to give a cosmetically attractive end to each link of the arm.

Choice of actuator is a major consideration. For a robot three basic forms of drive may be considered - electrical drive, hydraulic and pneumatic. Of these pneumatic is not suitable for good positional control, being usable mainly in a "bang-bang" two position arrangement. Servo controlled pneumatic systems are difficult to regulate, due to the compliance of the system. Pneumatic systems are also noisy. Hydraulic systems give a good power to weight ratio but have numerous practical problems which make them unsuitable for a relatively cheap robot in a domestic situation. Perhaps the major problem is the possibility of leaks. Other problems include the need for filtration of the fluid, elimination of air bubbles, the need for a central distribution unit, and maintenance problems. Electrical power is ideally suited to this kind of robot system.

Having decided to use electrical actuation there are still decisions to be made, particularly between dc servo motors or stepper motors or (for the vertical actuator) a commercial linear actuator unit. The motors may be mounted in the base, with drive to each of the actuators. This gives a light weight arm with low inertia with simplified electrical connections, but a complex mechanical assembly. Alternatively the motors may be mounted at each of the actuators. The latter arrangement was chosen, using relatively low powered, light weight components. This is possible due to the jointed cylindrical configuration where the rotary joints do not act against gravity.

ROTARY ACTUATOR

For positional control of a rotary actuator there are a number of options to be considered of motor and speed/position feedback.

Stepper motors offer positional control in open loop mode. However the positional reliability is not good, due to the possibility of motor stall (a problem encountered with the Atlas system). An encoder could be mounted to the motor to provide reliability of position feedback, but this adds to cost and weight. Although stepper motors offer high torque with relatively little gearing, they are of low resolution. To achieve the required output resolution it would be necessary to use either a gearhead (with increased cost and weight), or to use complicated microstepping circuitry. Stepper motors have a relatively poor power to weight ratio.

DC servo motors can be used with a combination of gearheads, positional encoders and tachometers, to give smooth, quiet performance with reliable positional feedback and control. Tachometers, for constant speed performance, are not necessary. Their function may be replaced either by the differentiation of the signal from a position encoder (preferably mounted directly on the motor), or through the use of current feedback circuitry to provide constant speed. Encoders to provide positional information may be either mounted directly on the motor or further down the gear train. If mounted on the motor a low resolution unit may be used, but there may be problems of backlash in the gear train. An encoder mounted downstream will need to be a higher resolution.

Encoders may be of three types, potentiometer, incremental optical, or absolute optical. Potentiometer types require an analogue to digital encoder for use in a digital control system and tend to be less accurate. Optical types give good digital accuracy with quadrature increasing the resolution. Absolute optical encoders are expensive but do not require the system to be reset each time.

The system chosen for the rotary actuators was to use a dc servo motor with integral gearhead and high resolution incremental optical encoder downstream. Speed control was to be using current feedback circuitry.

Trial joints

The axis of the rotary joints in the chosen geometry is vertical. The easiest orientation of the motor is therefore also vertical, driving though gearhead and pulley/belt gear stages. The penalty of this arrangement is that the height of the motor/gearhead must be accomodated. This will require the motor to protrude above the section of the arm. For aesthetic reasons it was decided that the motors should lie along the line of the arm within the arm structure. Turning the axis of rotation would therefore require either a bevel or worm and wheel gear stage. The use of a non-backdrivable worm and wheel stage is not recommended due to the danger of the arm drive train being damaged if it was forced in a horizontal direction. A bevel gear stage was therefore chosen.

The basic design chosen was therefore to have a motor gearhead unit driving a bevel gear stage. To the bevel would be fixed the encoder unit. The bevel would transmit drive to the joint using a pulley/belt drive. This arrangement can be repeated for each of the rotary actuators, the use of common components and design simplifying the design process and eventually giving lower costs due to quantity discounts.

Trial joints were designed and built to test out the performance and control. Priorities in the design were adequate performance, low cost components, simple machining and aesthetic appearance.

Trial joint 1: (Fig. 9.2)

6W motor with 60:1 gearhead.
Flexible coupling.
Bevel gear stage.
Timing belt (trapezoidal), and pulleys, ratio 60:12, with tensioning.
Final rotation through two deep groove ball bearing races.
Hohner X Series incremental optical encoder (360 line) mounted to large bevel through a flexible coupling.
Cabling external.

Trial joint 2: (Fig. 9.3)

6W motor with 60:1 gearhead (as 1).

Bevel gear stage (as 1)

HTD belt, and pulleys, ratio 60:12, with tensioning.

Final rotation through one ball bearing races and one plastic bush.

Hewlett Packard encoder (unenclosed) with code wheel mounted direct to bevel shaft.

Cabling internal.

One of the problems with the first joint was the location of the encoder unit outside of the section of the arm. The Hewlett Packard encoder was subsequently sourced. Being of an unenclosed construction the code wheel is only connected to the bevel shaft, so there is no need for the flexible coupling which had been incorporated to eliminate side loads to the encoder. The whole unit can be mounted within the section of the arm. In order to maintain the clean exterior the cables were routed internally. Another major advantage of the HP encoder unit was a saving in cost.

It was decided that the flexible drive between the motor gearhead and the small bevel was not necessary, the gearhead being able to handle the side loads. This allows the motor to be located closer to the bevel. At the same time the spacing between the two pulleys was increased, allowing easier tensioning of the belt. The tensioning is a one off adjustment to allow for machining tolerances and does not need to be readjusted in use. The timing belt was replaced by an HTD drive belt which can carry greater loads, yet is cheaper.

<u>Final joint</u>

The final joint was essentially the same as Trial joint 2, but with a smaller 3W motor. The bevel gears previously supplied were not entirely satisfactory in quality, and so were replaced by gears from an alternative supplier, Davall. The plastic bearing used in joint 2 allowed too much play, and was replaced by a ball bearing race.

For the final manipulator this joint is repeated three times at shoulder, elbow and wrist. On each of the joints a different ratio gearhead was used, reflecting the different inertias and speeds seen by each motor. Fig. 9.4a shows the shoulder and elbow actuators mounted back to back in the upper arm and Fig. 9.4b shows the wrist actuator in the lower arm.

The figures show the general construction of the joints using the standard aluminium extrusions. Motors and bearings of horizontal shafts are mounted on sections of the "U" channel mounted across the section of the arm. The side "U" channels are machined away to clear these transverse sections. Bearings of vertical shafts are screwed directly to the upper and lower plates. The actuator may therefore be fully assembled before the side channels are fixed.

One further modification for the final shoulder joint was to increase the spacing of the upper and lower bearings to decrease the side loads on each.

Details of the drive train are as follows.

Motor:	Maxon "F" motor. 21 30 908.	
	Power rating:	3W.
	Nominal voltage:	15v
	Stall torque at 15v:	4.9 Nmm
	No load speed at 15v:	5000 rpm
Gearhead:	Spur gearhead. Maxon 2930 series.	
	Shoulder ratio:	60:1
	Elbow ratio:	30:1
	Wrist ratio:	15:1, (replaced by 30:1)
Bevel gears:	12 teeth, 32 DP. / 48 teeth, 32 DP.	
Drive belt:	HTD belt, 3mm pitch, 9mm wide, 84 teeth	
Pulleys:	12 / 60 teeth,	
Encoder:	Hewlett Packard incremental optical encoder	
	HEDS 9100 Encoder module	
	HEDS 5100 Code wheel - 500 lines	

Evaluation

The design of the rotary actuators is considered very successful. There was concern over the resistance to rotation in some of the joints. This was a particular problem with the wrist. This was overcome by increasing the gearing ratio of the gearhead to give higher torque.

WRIST ROLL

The wrist roll is a very simple design, and did not progress through any trial actuators. The arrangement is shown in Fig. 9.5. The motor/gearhead unit is parallel with the roll axis and drives the roll through a single 2:1 spur gear stage. The encoder is mounted on the small spur gear, therefore rotating at the same speed as the motor gearhead output.

Details of the drive train are as follows.

Motor:	Maxon "F" Motor 21 30 908 (as above)
Gearhead:	Spur gearhead. Maxon 2930 Series. 500:1 ratio
Small Spur:	20 teeth, 0.7 mod
Large Spur:	40 teeth, 0.7 mod
Encoder:	Hewlett Packard incremental optical encoder HEDS 9100 Encoder module HEDS 5100 Code wheel - 500 lines

Evaluation

The roll actuator is simple, and has not caused any problems. However the gearhead of the motor might be damaged if a high external torque were applied. There should be a better matching of gear ratios and torque specifications.

VERTICAL ACTUATOR

Having decided above that electrical drive would be used, there are a number of options that must still be considered for the vertical actuator. One attractive option is to use a commercially available linear actuator. This however was discounted early, because of the difficulties of obtaining a unit with adequate stroke, within an overall length of about 24" and at acceptable cost. The vertical travel required is 18". The choice between stepper motor and dc servo motor was made in favour of dc servo motor. Many of the reasons quoted above for the rotary actuator are relevant. There are benefits of using similar components and drive electronics throughout.

Three methods of transferring the rotary motion of the motor to linear motion were considered. A ball screw (with either the ball race or the lead screw driven) may be used, a chain drive over a sprocket or similarly a belt drive over a pulley. Of these options a ball screw was rejected since the high speed reduction ratio inherent in a ball screw would have required a high speed drive from the motor/gearhead. A ball screw would also be relatively expensive. The chain or belt drive methods are similar but the use of a belt seemed more appropriate for the relatively low tensions and domestic environment.

Trial actuator

The trial actuator (Fig. 9.6) used belt drive, over two pulleys. The motor drives the lower pulley. The optical encoder is a 360 line Hohner unit mounted to the output of the motor gearhead through a flexible coupling to eliminate side loads. Rotation of the post is resisted by a fixed steel post parallel to the main post, running in a bearing cantilevered to the moving main post.

One of the major problems considered was how to provide linear bearings for the vertical post at acceptable cost. The use of a commercial linear ball races would have been unacceptably expensive due to the cost of providing a 2" diameter ground steel shaft of the required length. The cheapest option, which was used, was the use of an oil filled plastic bearing material (Railko PV80). Two bearings were used, at a spacing of 5". The sliding post, which supports the arm was made of 2" diameter stainless steel tube, available relatively cheaply for architectural applications. There was a certain degree of ovality which caused uneven sliding in the bearings. However to have used a machined post would have been prohibitively expensive.

The arm is counterbalanced by a weight, over pulleys. A 5 kg weight is shown in the photograph, but the estimated weight of the complete arm and load to be counterbalanced is 10 kg. The counterbalance is attached to the arm itself. This arrangement decreases the load carried in the belt.

The motor used was a 40W motor driving into a 66:1 gearhead. This relatively large motor was considered adequate to overcome the friction in the oil loaded plastic bearings with excess torque being limited by the current limit trip on the control board. The motor does not need to overcome the weight of the arm because of the counterbalancing. In practice the friction was worse than the manufacturers figures suggested and the motor required all its available torque.

Final actuator design.

For the final design (Figure 9.7) a major change made was to use a constant tension spring for counterbalancing, rather than the hanging weight of the trial actuator. Besides being more robust, the constant tension spring allowed for a much more compact design as can be seen by comparing the illustrations. One possible disadvantage of using a constant tension spring is the limited life. The stated fatigue life of 15000 cycles corresponds to only 50 cycles per day for a year. Therefore regular planned replacement may be necessary.

The separation of the plastic bearings was increased, and they were mounted in a box structure for added rigidity.

The motor was moved to drive the upper pulley to allow space at the bottom for the constant tension spring assembly. The encoder is an enclosed unit, mounted on the bottom pulley.

Details of the drive train are as follows.

Motor:	Maxon "F" motor. 22 60 813.	
	Power rating:	40W.
	Nominal voltage:	24v
	Stall torque at 24v:	816 Nmm
	No load speed at 24v:	3660 rpm
Gearhead:	3 stage Helical cut spur gearhead.	
	Ratio:	66:1
Drive belt:	HTD belt, 5mm pitch, 15mm wide, 254 teeth	
Pulleys:	30 teeth, Steel with flanges	
Counterbalance:	Tensator constant tension spring. 21 lb load	
Encoder:	Hewlett Packard HEDS 5500	
	Incremental optical encoder with 500 lines	

Evaluation

The vertical actuator has not been entirely satisfactory, due to the high friction in the oil loaded plastic bearings. Besides high friction this has also led to a stick-slip performance. One of the results of this high friction has been the use of a higher power motor than would otherwise be required. This has led to the gearbox being overloaded when driven against the endstops and failing on a number of occasions. Because of the high motor torque available from the motor there has been concern over this torque giving a high force at the vertical actuator which might trap and injure a hand placed on the desk top. For the future rolling bearings should be considered, with a lower powered motor.

CABLE MANAGEMENT

It has been stated by an experienced robot designer that the key to cable management is to start with the cabling, and then to add the mechanism later. In our design, particularly with motors mounted within the arm, cabling was considered from the very beginning.

The cables (round jacketed flat ribbon cable) are routed throughout, within the structure of the arm. The cables can be separated to dismantle the arm at each of the joints. At each of the separation points signal/power wires are taken off as required.

Initially two large cables carry power for the motor and signals from the encoders, switches and sensors. Both cables use round jacketed flat ribbon cable. The power cable is a 34 way cable of overall diameter .39" and the signal cable is a 40 way cable of overall diameter .41". For the power cable 24 separate wires are used to take the current for the large 40W motor. Thus the cable soon decreases to a 10 way cable (diameter .25"). 2 wires come off the cable for each of the motors in the upper arm. For the signal cable 8 wires come off for the vertical actuator, and the remainder of the cable splits into 16 way cable (diameter .29"), and then 10 way as further signal wires are taken off. This is illustrated in Fig. 9.8.

Where the cable enters the bottom of the vertical post a commercial cable tidy product "Lapp Power Chain" is used. This neatly guides and contains the cable from a fixed point on the frame of the actuator to the bottom of the post. At the rotary joints a rotation of approximately 340 degrees is allowed. At each of the joints space is provided to allow the cable to twist up.

Evaluation

The cable management has been satisfactory. However assembly of the cabling is time consuming, and may be too expensive for batch production. The use of a serial link to communicate up the arm may be considered in future.

COMPLETED ARM

Assembly of the various joints described above involves many extra details which must be considered. Cable management, as described above is one of the major areas.

Various switches and sensors are incorporated to locate the arm in space. For each rotary joint mechanical endstops are fitted to limit the rotation. These are chosen from a safety point of view to restrict the motion of the arm near the user. They are also positioned to stop the arm overhanging the desk top near the parked position. The mechanical endstops are provided by a peg moving against a steel screw. The peg is covered by silicon rubber sleeving, the compliance reducing shock loading on the bevel gears.

For resetting the absolute position of the arm when power is first turned on, optical sensors were used to detect either the edge of an adjacent link of the arm, or a marker on the desk top in the case of the shoulder joint. (Fig. 9.9). The sensors were angled infra-red proximity sensor units, which in theory were able to give good resolution of the position. In addition to these accurate position sensors, microswitches were also incorporated to provide approximate positioning of the arm, prior to using the more accurate sensors.

For the vertical actuator also, optical switches were used for accurate position setting, with microswitches for approximate positioning. A rubber faced mechanical endstop was fitted at the bottom of the motion. At the top of the motion a microswitch cuts out power to the motor.

The arm is designed such that the motors and gearing etc can be fitted to the upper and lower plates, with the side channels removed. This makes for easier assembly and maintenance. Fig. 9.10 shows the upper arm separated into individual links, with the side panels removed. With the arm in this state, the wiring can be connected up. Fig. 9.11 shows the completed arm.

A summary of the drive train is given in Table 9.1.

The arm was weighed after wiring had been completed.

Vertical actuator	11.5 kg
Arm (excluding gripper)	6.15 kg
Hugh Steeper gripper	.35 kg
BIME gripper	.85 kg

The lifted weight of the arm (with BIME gripper) and vertical post is 8.5 kg.

Details of the costing of the arm are given in Table 9.2

Evaluation

The overall concept of the arm is considered successful. Many detail points have been mentioned above, and others will be mentioned in the context of user evaluation. The use of optical sensors for positioning proved unreliable in bright sunlight. In practice therefore the system has been reset by driving against the mechanical endstops until the motor current limit trips. On the vertical and roll actuators the microswitches have proved reliable and accurate enough for positioning. Though not recommended for future versions these methods of resetting have proved adequate in practice. Further comments are made in the software description section. Further thought should be given to a reliable zeroing system.

One feature not considered in this first arm, but of importance for production versions is the ease of maintenance in the field. As commented above the constant tension spring in the vertical actuator may need routine replacement. The drive belts in the upper arm are not easily replaced if they should break, without dismantling the whole arm.

Safety has always been a major issue in robotics due to tha ability of a robot to move freely in three dimensions, often with considerable inertia and potential force. While strict safety standards have been drawn up for industrial robots, no such standard exists for rehabilitation robots. The major difference between industrial robotics and rehabilitation robotics is that in the former the system is designed to keep the human out of the working envelope, while in the latter there is usually necessary physical interaction. Moreover a disabled person is not able to avoid a moving robot. The approach to safety for the Wolfson robot is outlined, with a hazard analysis in Appendix 2.

Details of drive train.

	Motor to encoder	Encoder to output	Overall ratio	Movement per pulse
Vertical	66:1	120mm/rev	1.82mm/rev	.075mm
Shoulder	240:1	5:1	1200:1	.036 deg
Elbow	120:1	5:1	600:1	.036 deg
Wrist (1)	60:1	5:1	300:1	.036 deg
Wrist (2)	120:1	5:1	600:1	.036 deg
Roll		2:1		.009 deg

Table 9.1

Prototype costing (Mechanical components).

	Vertical	Shoulder	Elbow	Wrist	Roll	Gripper	Total
Motor/ Gearhead	£166	£51	£51	£51	£54	£32	£405
Encoder	£37	£40	£40	£40	£40	£40	£237
Gears/ belts	£18	£31	£31	£31	£12	£60	£183
Bearings/ bushes	£9	£25	£25	£25	£15	£26	£125
Other components	£43	£3	£2	£2	£3	£6	£59
Metal	£38	£24	£16	£22	£8	£2	£110
Total	£311	£174	£165	£171	£132	£166	£1119

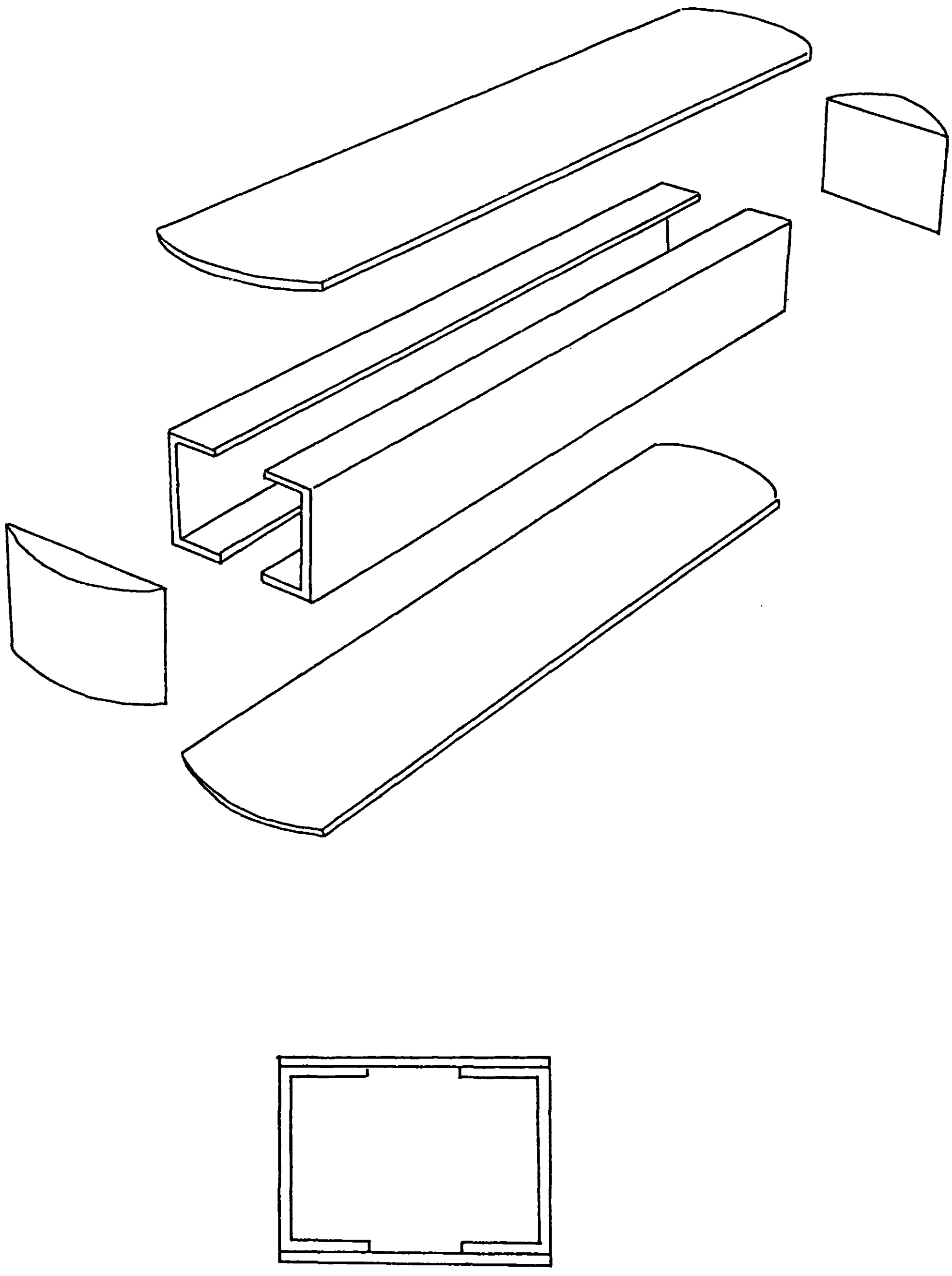
These figures are exclusive of VAT at 10-Jan-90.

Components are 1 off prices.

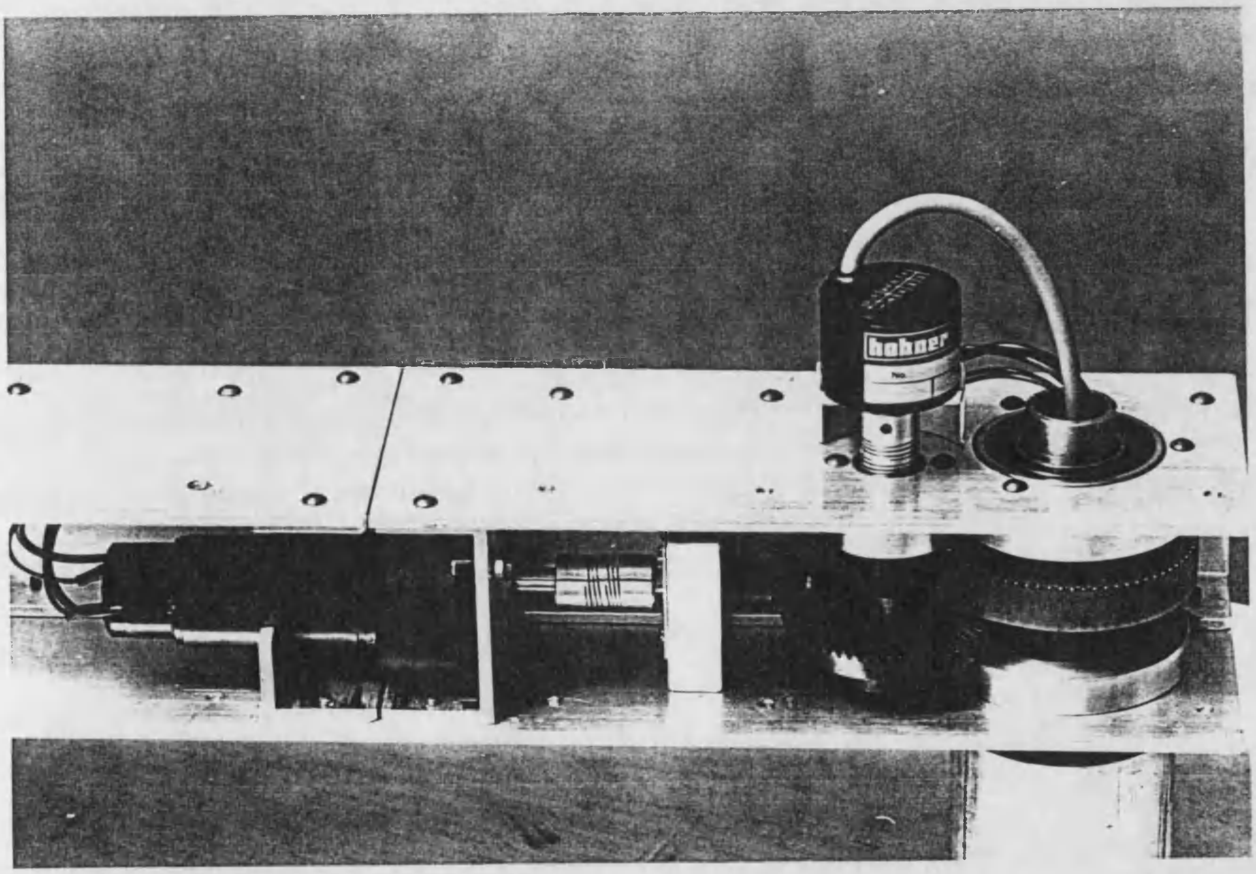
Cables and connectors are not included.

The gripper design is described below.

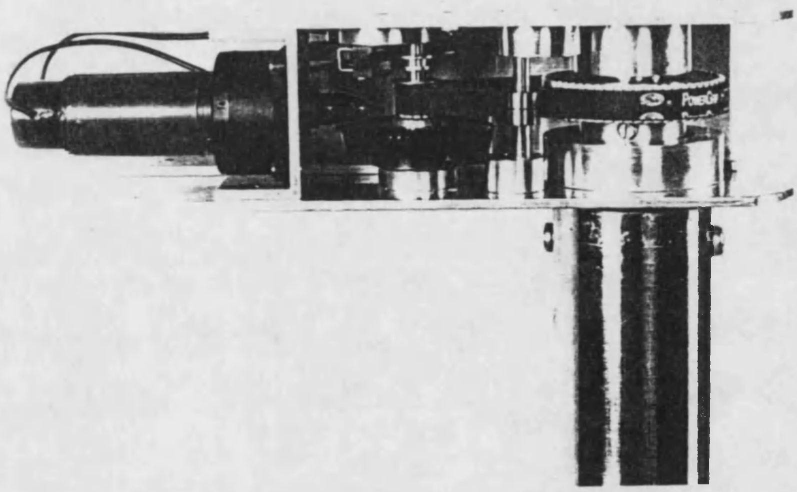
Table 9.2



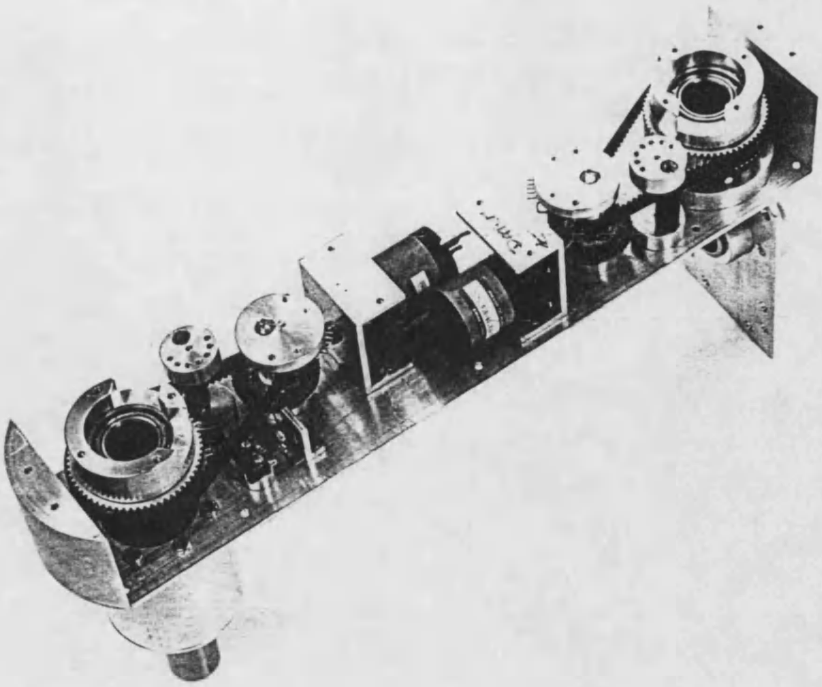
Basic construction of arm structure   Fig. 9.1



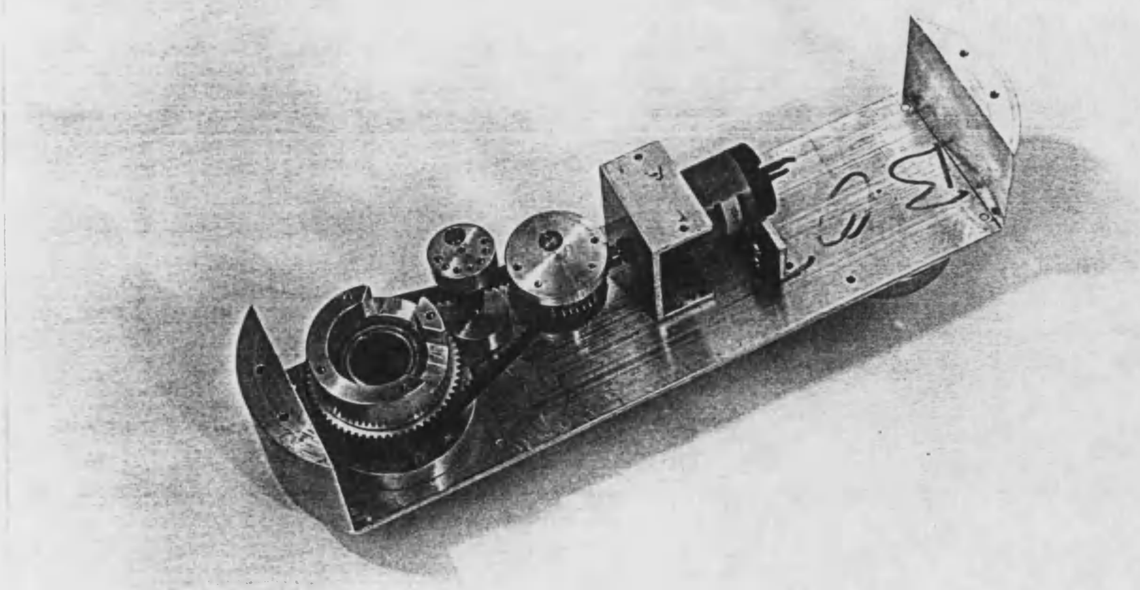
Rotary trial joint 1 Fig. 9.2



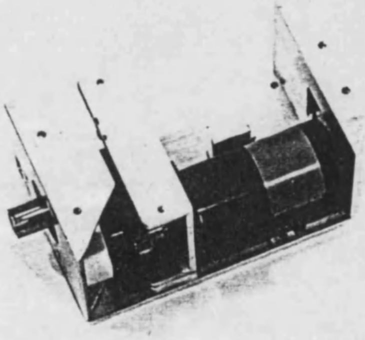
Rotary trial joint 2 Fig. 9.3



Upper arm with rotary actuators Fig. 9.4a

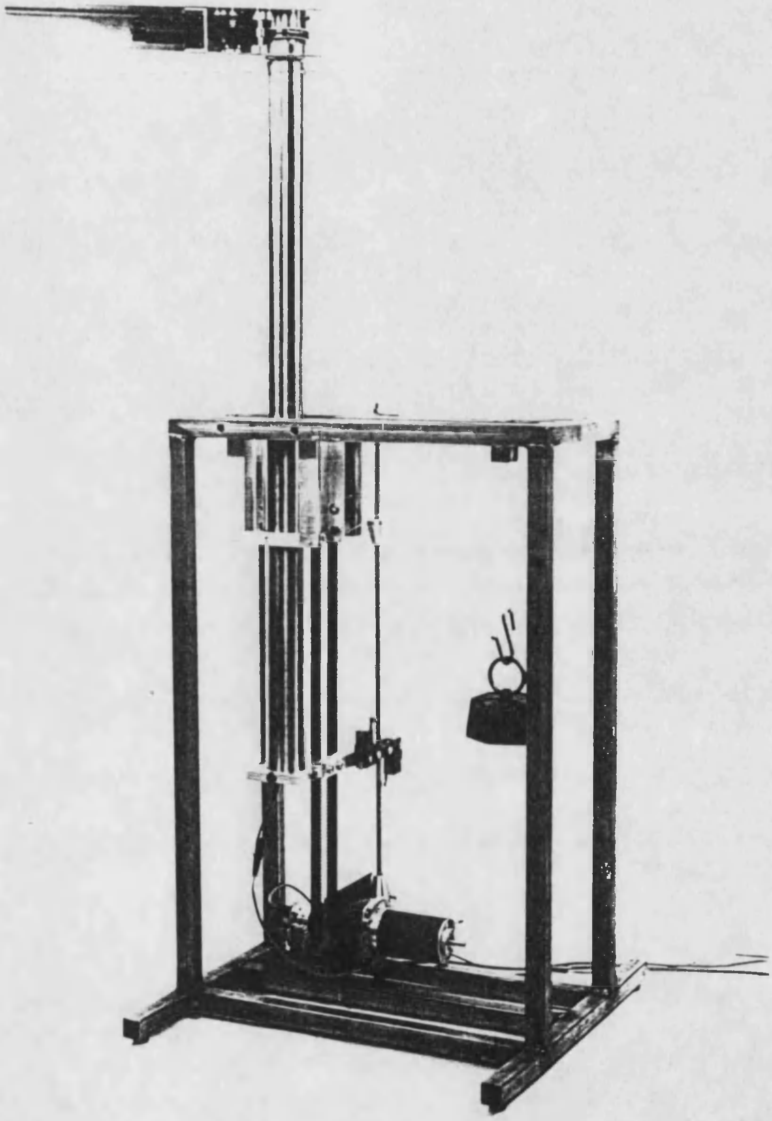


Lower arm with rotary actuator Fig. 9.4b

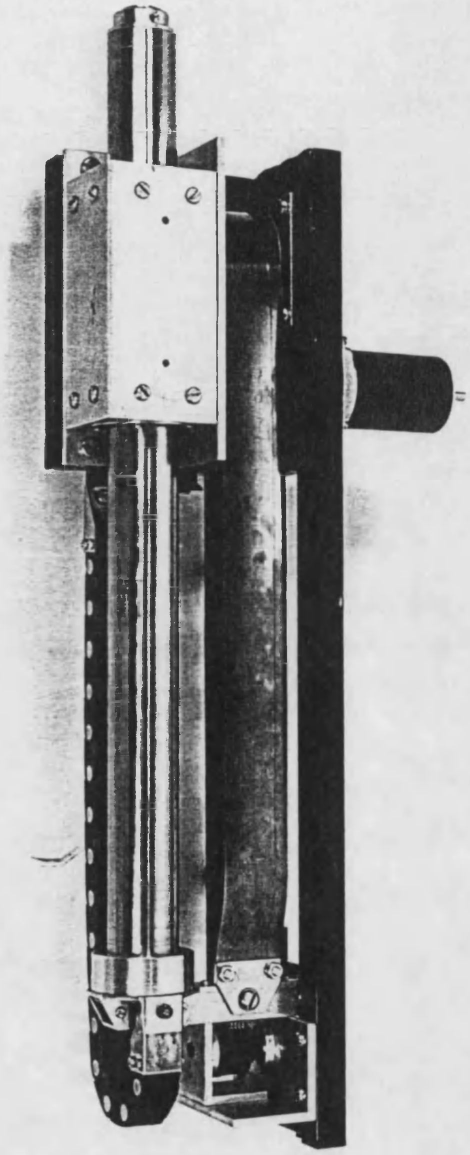


Wrist roll actuator

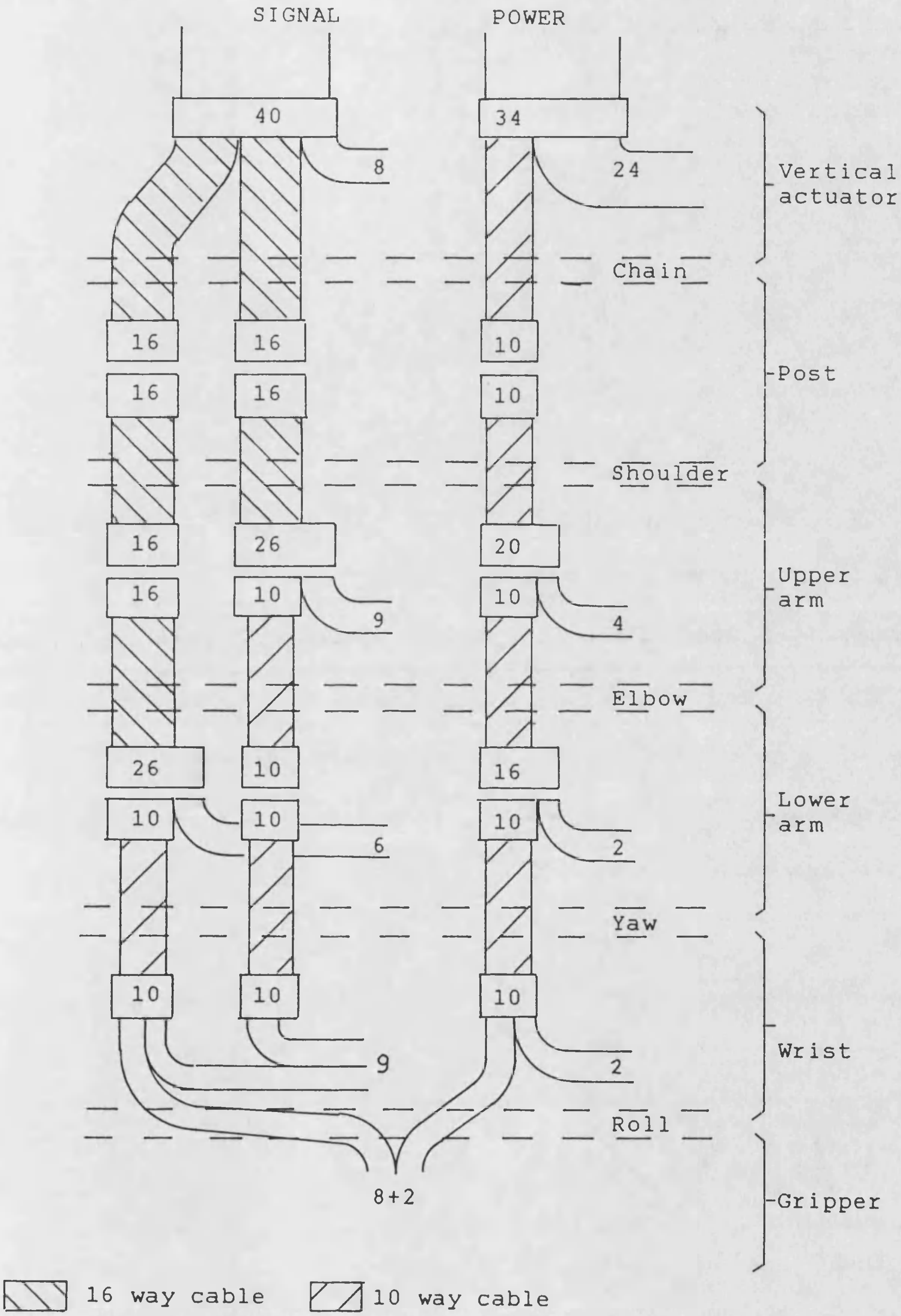
Fig. 9.5



Trial vertical actuator　　　　　　　　　　Fig. 9.6

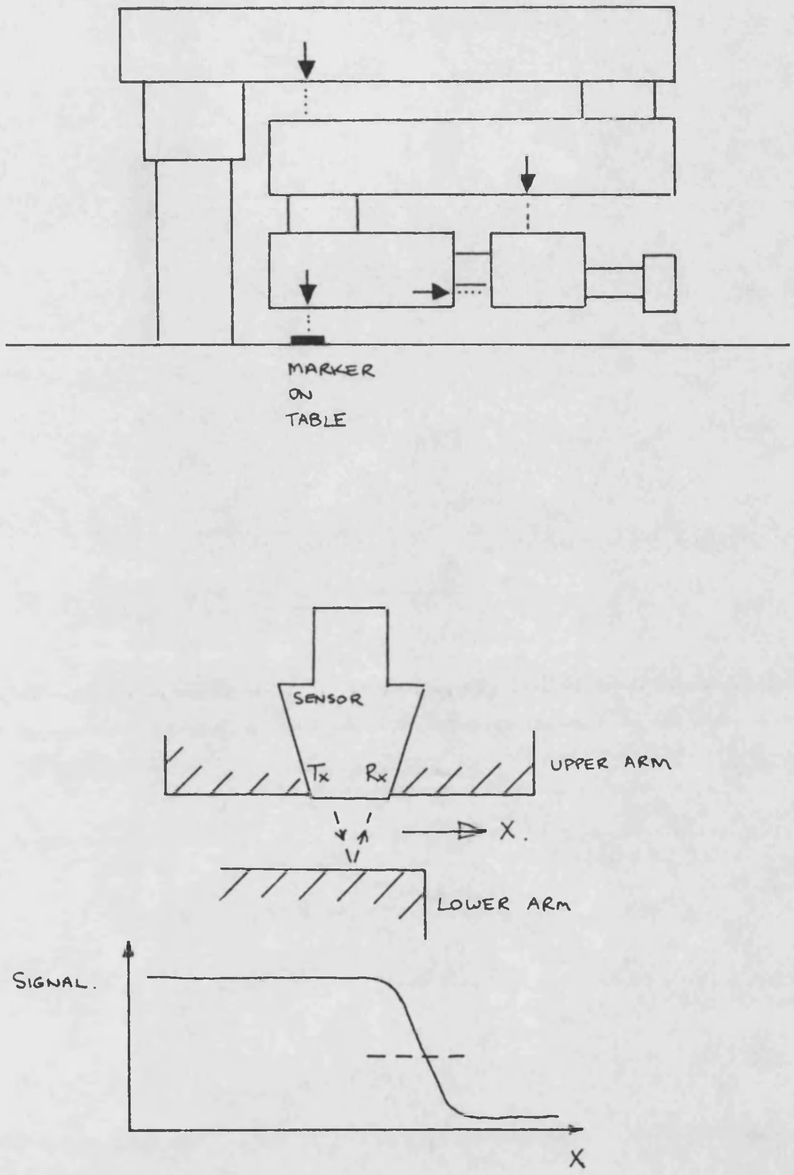


Vertical actuator Fig. 9.7

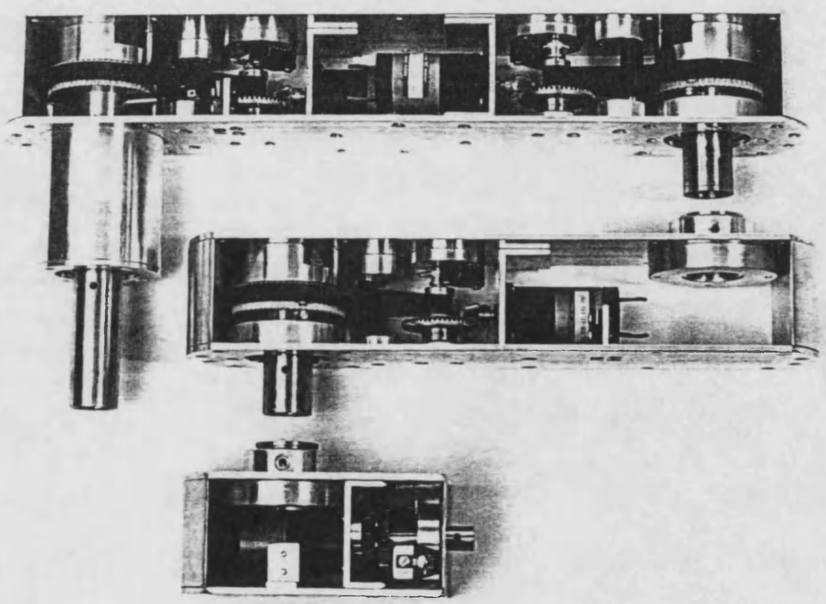


Cabling layout

Fig. 9.8



Positioning of Opto Sensors Fig. 9.9



Upper, lower arm and wrist,
with side panels removed

Fig. 9.10

Completed manipulator mounted on workstation. Fig. 9.11

Chapter 10. WOLFSON WORKSTATION SYSTEM - GRIPPER

INTRODUCTION

A prosthetic hand was initially used as the gripper for the manipulator. This did not prove satisfactory. Subsequently a simple two jaw gripper was designed. Initial plans were to provide simple sensors for intelligent gripping but, though described below, these were not implemented.

SPECIFICATION

The specification for the gripper was determined from the operational requirements, the geometry of arm to which the gripper was to be fixed, and the control methods to be employed. Tasks identified from the previous trials included the picking up and insertion of objects and the pushing of switches. More complex manipulations are not considered appropriate for the type of system. Many of the objects to be grasped are flat (eg tape, book, computer disc), though cylindrical objects will also be handled, either parallel to the axis of the gripper, or perpendicular to it. Due to the lack of pitch the jaws should be able to pick up both from the table top and from a rack system without pitch freedom.

Use of the gripper is to be at the control of the user through the menu scanning system, though a simple algorithm to locate and then grasp an object would be considered. External sensors would be required for this algorithm to detect the object. Force sensing of the grip force might be required. Also internal sensing of the gripper joint positions would be required.

The cross section of the gripper where it fixes to the wrist should be of the same cross section, and the aesthetics should be in keeping with the appearance of the overall arm. Overall length of the gripper is limited by the need for the arm to fold compactly.

A qualitative specification based on the above requirements and experience with the earlier system is therefore:

Grip force: 20 N

Time to close: < 2 seconds

Internal position sensing to give resolution of better than 1 mm at the jaws.

Cross-section: 2.25" by 3"

Overall length: 7"

Maximum opening of jaws: 3.5"

PROSTHETIC HAND GRIPPER.

A prosthetic hand gripper (Fig. 10.1) was provided for our use by Hugh Steeper Ltd. This has a "hook" shape, as commonly used for prostheses. The two jaws operate independently, the first giving high speed and low torque, the second giving high torque. Both jaws are non-backdrivable. Internal logic controls the actuation of the two jaws from a simple logic open/close signal.

The gripper was fitted to the robot arm, but was found unsatisfactory. The non symmetrical shape, though ideal for a prosthetic hand was not appropriate for a robot gripper. The jaw shape, without parallel closing surface did not give adequate grip force in a shear plane. Lack of position feedback was not acceptable for the control/replay strategies planned.

DESIGN CONCEPTS CONSIDERED

The basic decision was made that the jaws should be of a simple design due to the need to keep the overall cost down, and also because of the limited control signals from the user. A basic two jaw system should be used. Within this constraint various options could be considered. The jaws could be separately actuated, actuated together through gearing, or one of the jaws could be fixed. Three different linkage designs could be employed; the linkage could be single link, parallelogram linkage, or a linear sliding linkage.

The objects to be gripped are likely to be either cylindrical or flat. The gripping of flat objects ideally requires parallel jaws to give surface contact, though line contact or three point contact might be acceptable. If a single linkage design was used a flat jaw piece would need to be self aligning. Cylindrical objects require a notched or concave shaped surface, though a compliant surface might give sufficient shear force to provide adequate location. The design chosen must be able to accomodate both flat and cylindrical objects.

The basic design chosen was to have a symmetrical design with parallelogram linkages. The symmetrical design was considered most appropriate for ease of operation. The use of a single motor geared to both jaw linkages is necessary for symmetrical operation, and allows the use of a single motor/position encoder. Flat jaw pieces would be used, with a compliant rubber surface to facilitate grasping of cylindrical objects in any orientation.

DETAILS OF GRIPPER

The gripper layout is shown in Fig. 10.2, and a photograph in Fig. 10.3. The overall length is 6.7" and the cross section is the same as the arm cross-section. Maximum gripper opening is 3.5". The outer link of the parallel linkage is a "U" section, giving a neat appearance and good structural rigidity. It is not powered. The inner link is a single flat member and is screwed directly to the driven spur gears.

Since the arm has no pitch degree of freedom, the jaws must be able to pick up off the table top with the axis horizontal. This is arranged by extending the jaw pieces downwards to just below the bottom of the wrist. Since the width of the jaw pieces must be limited so as not to obstruct the manipulation task (for example insertion into a slot), the axis of the jaws must be off centre. The bump on the jaw piece is to facilitate the pressing of buttons or pushing a tape/disc into a slot.

The motor is a small (16mm diameter) 1.2W motor running at a no load speed of 12000 rpm at a nominal 24V. In order to achieve the required grip force, and operation speed a large gear ratio is required. The worm and wheel gearing (Fig. 10.4) contributes a ratio of 24:1 to the overall gearing. This gearing arrangement also turns the direction of rotation through 90 degrees, allowing the motor to be arranged across the gripper, giving short overall length. Another benefit of the worm & wheel gearing is that it is non-backdrivable. Thus if power is lost the gripper will not release and drop any object in its grasp.

Motor details: Maxon "S" motor. 23 16 914

	Precious metal bushes.	
	Power rating:	1.2W
	Nominal voltage:	15v
	Stall torque at 24v:	3.3 Nmm
	No load speed at 24v:	19200 rpm

Gearing details:

	type	teeth	pitch	speed out	eff.	torque out
1.	spur	40:40	32 dp	n/4128	.9	Tx549
2.	spur	40:20	32 dp	n/4128	.9	Tx1220
3.	wormwheel	24:1	32 dp	n/2064	.5	Tx678
4.	spur	64:16	0.4 mod	n/86	.9	Tx56.5
5.	gearhead	21.5:1		n/21.5	.73	Tx15.7
	input	-	-	n	-	T

The encoder is a 500 line HP incremental optical encoder as used elsewhere in the robot. It is mounted on the worm shaft, and thus sees the motor rotation factored down by 86:1. With quadrature the output resolution is .0035 mm per quadrature pulse. The encoder is therefore vastly over specified, but was chosen at this stage for compatibility with the other encoders in the arm.

PERFORMANCE

The gripper was tested with a 24v power supply. The maximum gripping force measured was 21N. This is within specification. The time for closure from maximum opening was 2.6s. Although outside of specification, this was considered acceptable, particularly since the gripper normally will not be required to close from fully open to fully closed.

For comparison, the calculated performance was a load of 34N and a time to close of 1.8s. (For a lever arm of 2.1" (53mm) and a closure angle of 51 degrees). These figures are thus optimistic. An allowance was made for transmission inefficiencies of the gear stages, but not for other friction sources.

In operation the gripper performed satisfactorily. Once an appropriate rubber had been located for the grip surface the gripper was able to grasp objects with the available grip force without slip. The grip rubber incorporated an outer layer with good friction characteristics on top of a cellular rubber with good compliance characteristics. The lack of force feedback did not present a problem for the range of objects grasped.

Shortcomings of the gripper were due to the overall shape and geometry. The decision to use an off centre jaw axis was unsuccessful, as this complicated the use of the roll freedom. For roll about the axis of an object the object would need to be grasped off centre relative to the axis of the jaws.

The square shape of the gripper gear housing section led to poor visibility of the end of the gripper. Starting from the given cross-section, a more tapered design would be an improvement.

For any robot which might be used in a feeding situation it is important to eliminate food traps. The current design is poor from this point of view, particularly between the linkages, where the gears are clearly visible.

SENSOR IMPLEMENTATION

It had been intended to incorporate simple sensing in the gripper, but due to the pressure of time this was not implemented, though cabling was provided. The only feedback from the gripper is of joint position from the optical encoder. Force is limited by the current trip on the motor control board.

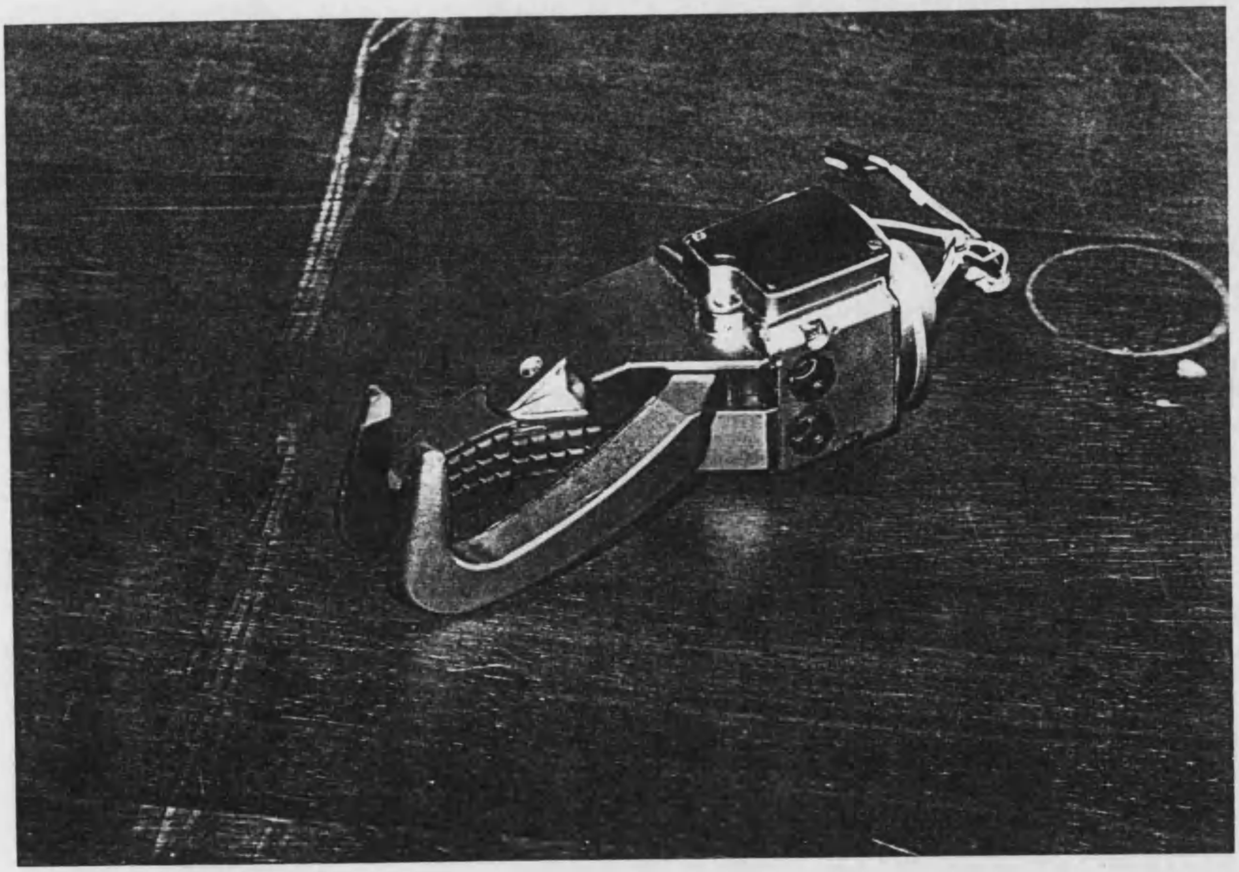
Grip force feedback might be incorporated by including a compliant torque link in the gear train. Thus initial movement of the motor would move the jaws, till they closed upon an object. Further movement of the motor would increase the load. Thus if the point at which the jaws close on the object is detected, the load can be calculated as proportional to the subsequent motor movement. Such a compliant torque link would need to be compact in order to not increase the overall size.

Various schemes were considered for the use of zero force touch or proximity sensors for a simple gripping algorithm. (Fig. 10.5). Sensors must activate with effectively zero force, must be cheap and compact. Two sensors were constructed and tested on the Atlas robot, but both had major shortcomings.

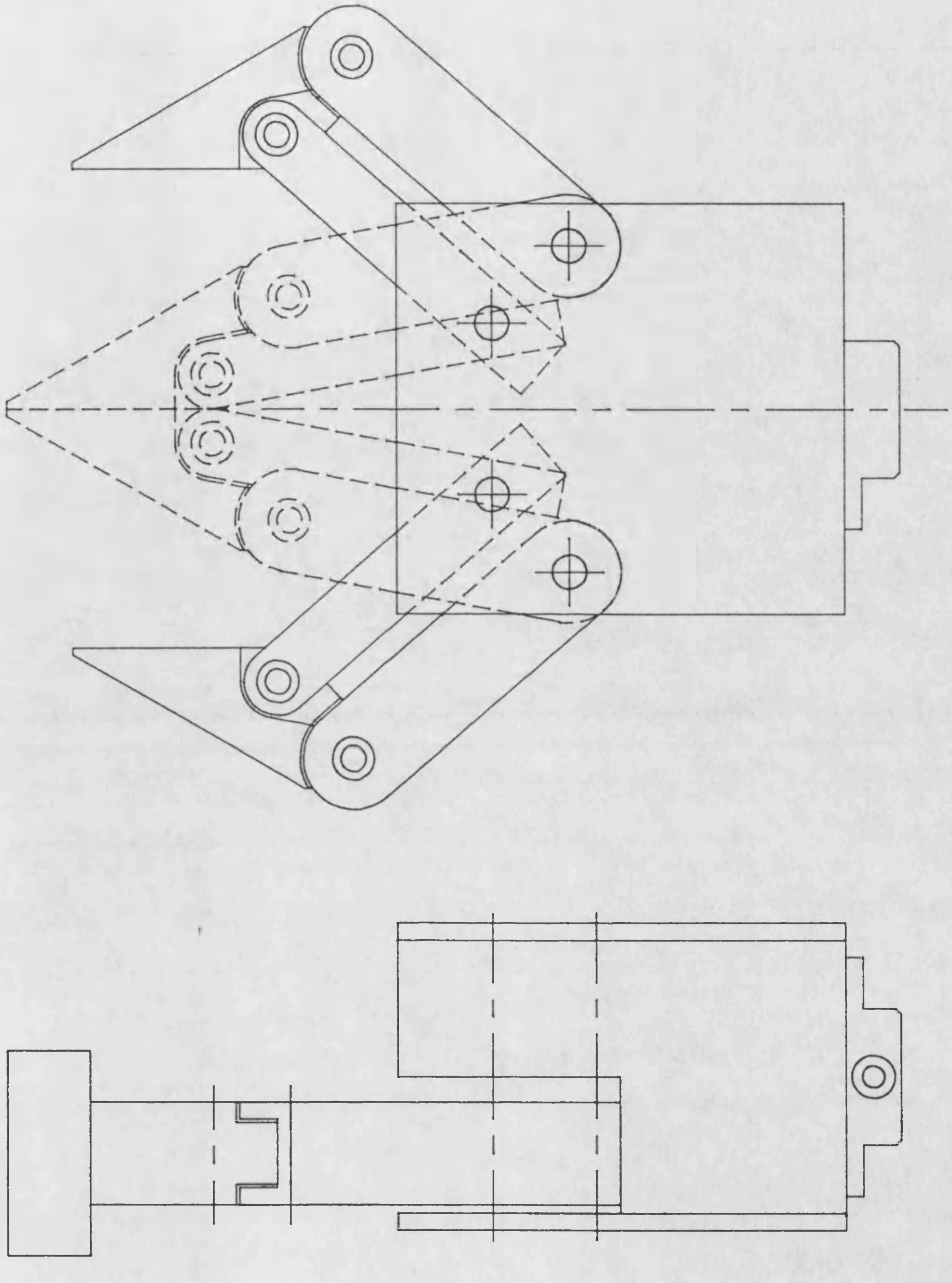
a) A trial touch switch was constructed using a gold wire contact, protruding slightly above the jaw surface, operating against a bus bar contact. This operated effectively at very low force, but was difficult to adjust, and would not operate if the object was not parallel to the jaw surfaces.

b) An infra-red proximity sensor was constructed using a commercially available device incorporating a transmitter and receiver in a small 5mm x 6mm casing. The sensitivity could be adjusted to activate when an object was within a millimetre of the sensor. The sensitivity however varied with the reflective properties of the object, and most importantly was not able to detect a black object.

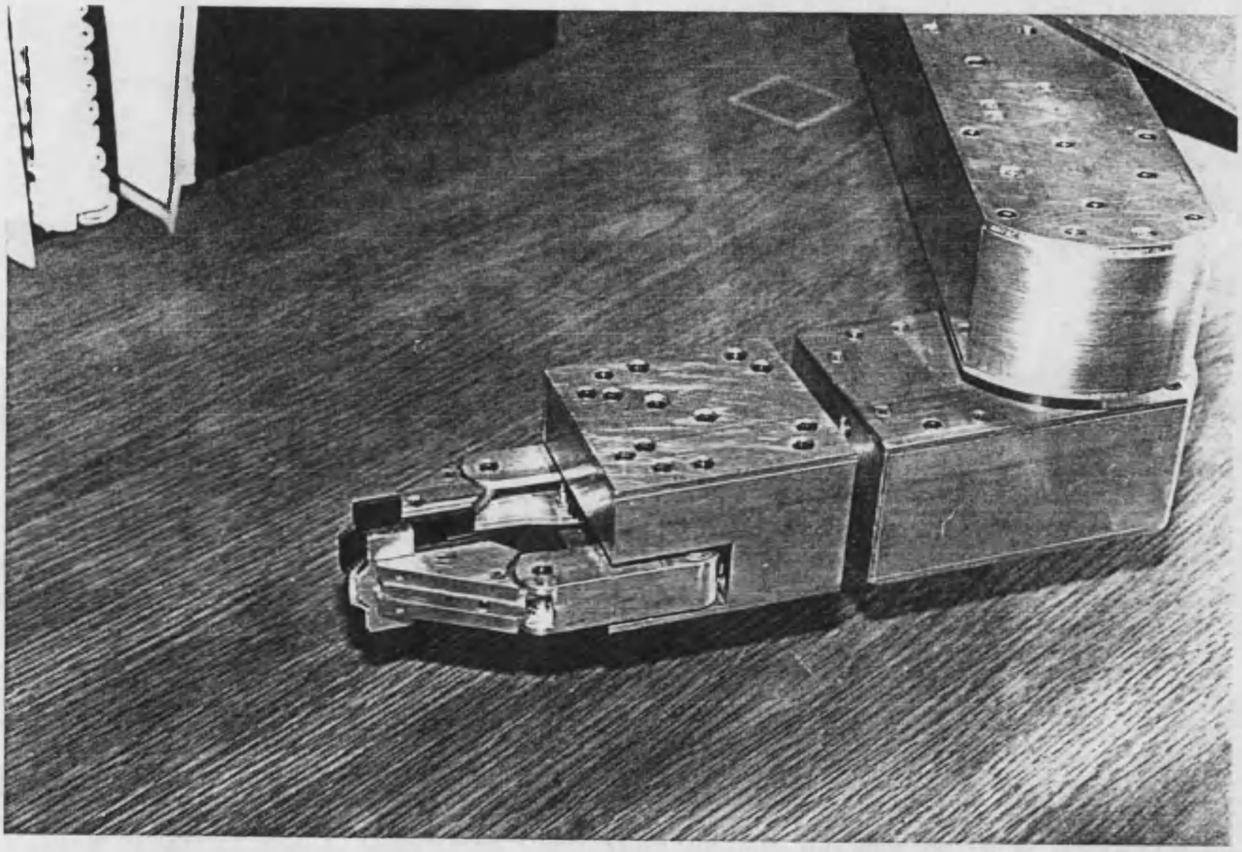
The scheme considered most promising for a future version of the gripper would be to use a pivotted jaw which activates a low force switch when any force is applied to it.



Prosthetic hand, as supplied by Hugh Steeper Ltd. Fig. 10.1

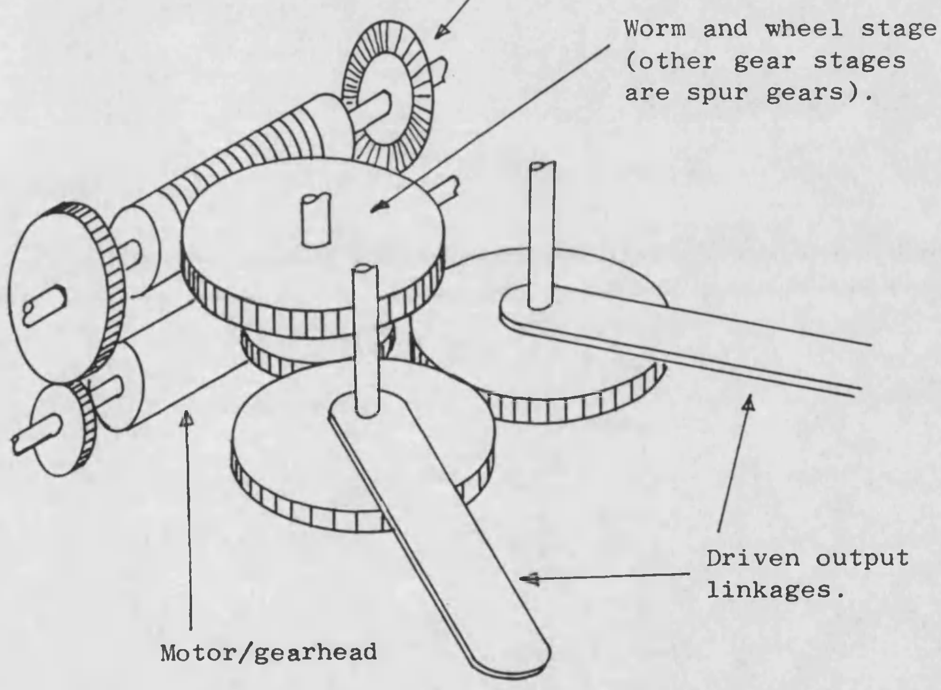


Wolfson Robot Gripper Layout. Fig. 10.2

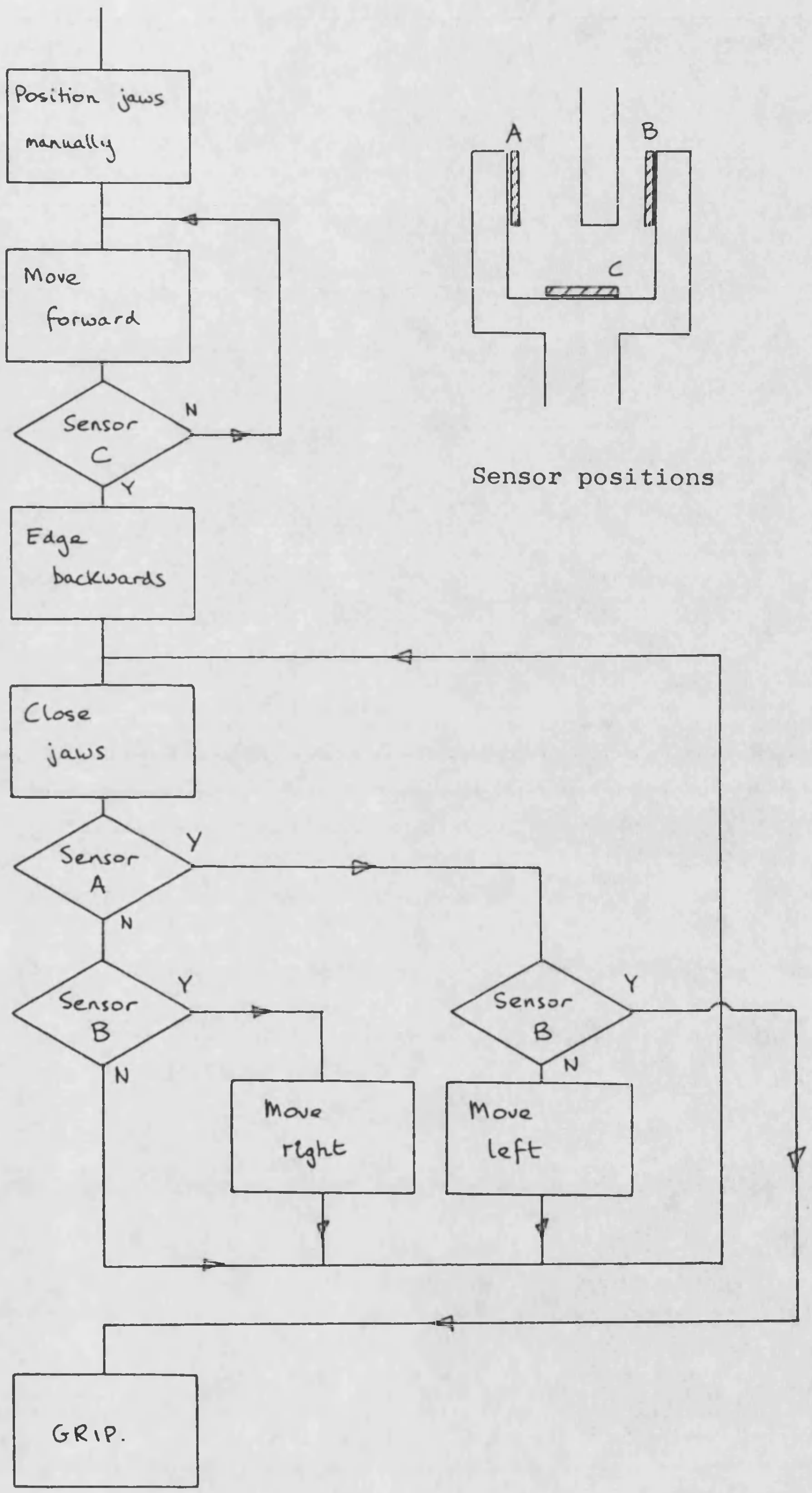


Wolfson robot gripper

Fig. 10.3



Gripper - Gear train arrangement. Fig. 10.4



Simple automatic gripping algorithm. Fig. 10.5

Chapter 11. WOLFSON WORKSTATION SYSTEM - ELECTRICAL HARDWARE

INTRODUCTION

The basic purpose of the electrical system is to send an analogue electrical power signal to each of the motors, and to monitor sensor, encoder and switch signals. The system is controlled by a EuroBEEB microprocessor card. This communicates with each of the motors through six motor control boards. These boards control the speed of the motor using the principle of current feedback. Other electronic units control the power to the system, monitor the sensors and control the mains outlet sockets. There is also an infra-red link for user input.

The whole system is powered from a single 13A domestic mains socket. Power supplies provide 24v and 8v supplies. The 8v supply is regulated to 5v on each of the electronic cards.

FUNCTIONAL REQUIREMENTS

The purpose of the electrical system is ultimately to send an analogue electrical power signal to each of the motors, and to monitor sensor, encoder and switch signals from the arm. The system is also required to provide mains power to the electrical sockets on the rear of the cabinet, for the environmental control facility and user microcomputer. A processor unit will determine the signals to be sent to the arm on the basis of command signals from the user microcomputer and on the basis of the position and states of the arm.

The system is powered by a single 13A domestic mains supply. This will need to be transformed to 24v for the motors, and to appropriate voltage(s) for the processor. The power-on requirements are that the whole system should turn on by the press of a single control switch. Control switches must then be routed to the user microcomputer to control the interface program. The system should turn off under the control of the user microcomputer.

These functional requirements are illustrated in the block diagram, Figure 11.1.

CHOICE OF PROCESSOR

Although the specification assumes the use of a microcomputer for the user interface and a processor card for the robot control, other options were also considered.

1. A rack mounted processor card handles all functions and drives a monochrome interface display: This is quite an attractive option. Costs are increased by the need to add a display interface card. This option is more attractive if the user does not need a microcomputer for vocational activities.

2. A rack mounted processor card handles all functions and drives a LCD display: The LCD may be driven directly by the processor, and so there is not the cost of a display interface card though software will need to be adapted. An LCD screen is compact, but is less easily readable, especially for those with poor eye sight (eg multiple sclerosis sufferers).

3. A processor to drive the robot, with user interface on a separate microcomputer: This is the most attractive option for those who require the use of a computer for vocational activies, though the robot interface must not compromise the regular use of the computer. This is however the most expensive option since the purchase or provision of a microcomputer is necessary to use the robot.

4. A microcomputer to handle all functions: Since microcomputers are readily available and inexpensive this is a

relatively cheap option. However it was not considered sensible to make the robot dependent on a particular microcomputer system.

In the short term it was therefore decided to use a processor card to control the robot and to store and manipulate the routines and to use a microcomputer as the user interface.

The requirements of the microprocessor were determined from the performance and memory requirements of the earlier BBC Microcomputer based system. Very approximately the memory usage by the earlier system was:

RAM memory	Variables	&1000	4kB
Battery backed RAM	Routines	&4000	16kB
EPROM/ROM	Motor control	&1000	4kB
	Menu/Interface	&1000	4kB
	Routine handling	&1000	4kB
	Utilities	&2000	8kB

This was fitted within the 64kB memory map of the BBC Microcomputer by the use of paged ROM.

This suggests that the approximate memory requirements of the system should be.

	RAM	B-B RAM	EPROM/ROM
User Interface	2kB	-	8kB
Robot control & routines	2kB	16kB	12kB

The earlier system had been based around the BBC Micro. In order to re-use as much software and hardware as possible the interface computer was initially specified to be the BBC Microcomputer. Software could also be re-used for the motor control functions if a 6502 based microprocessor card was used. The EuroBEEB card is ideal, being closely based around the BBC Micro, having a similar operating system, and having a BBC based development system cheaply and easily available.

The basic EuroBEEB II card has approximately 29kB of memory which may be configured in different ways as battery backed RAM or EPROM. In addition it contains a BASIC ROM, which may be replaced by another "language" ROM if required. Therefore no extra memory cards are required. Since the interface is on a separate microcomputer no screen memory is required, neither is a display interface card required.

Main features of the EuroBEEB II card are:

* 65C02 CMOS processor
* BBC BASIC IV
* BBC compatible operating system
* Four 28 pin memory sockets with a choice of memory devices.
* 32 kB RAM
* 8/16/32 kB EPROM for User Program
* Auto-Run on power-up facility
* 2MHz clock
* Interface facilities:

  Buffered RS 423 serial port

  6522 VIA with 16 digital i/o lines and 4 control lines

  Backplane connector
* Battery backup for CMOS memory
* Single +5 volt rail supply operation

OVERALL ARRANGEMENT OF ELECTRICAL SYSTEM

Assuming the use of a rack mounted processor card, it was decided to use a 19" rack to house the processor, a motor control card for each of the six motors, and various other cards for sensors and input/output. A custom backplane was used.

The various cards are decoded as blocks of memory in the processor memory map. The processor controls the Power Control unit through its parallel i/o port. Table 11.1 shows the memory allocations used.

One metal box would hold the power supply units, and another the power control unit.

The block diagram for the overall system is given in Figure 11.2.

The estimated parts cost of the electronics is £570 and of the power supply is £200. The cost of the EuroBEEB microprocessor card is £307. All prices are inclusive of VAT at August '89.

MOTOR CONTROL BOARD

There is a card for each of the six motors (Fig. 11.3). These are basically identical, though component values and other details have been varied for the different motors, particularly the vertical actuator motor. The block diagram for the motor control board is shown in Figure 11.4. The prototype was constructed on stripboard. When the design had been finalised double sided etched PCBs were designed and ordered. Some of the more major changes between prototype and final board are outlined below in the appropriate sections.

Current feedback speed control

The constant speed performance of the motor is based around the principle of current feedback [64]. This may be illustrated very easily by considering a circuit element which feeds back the motor current to the input.

$$Vm = V0 + K.I$$

where
Vm = Motor voltage
V0 = Input voltage
K = Feedback parameter
I = Motor current

The motor characteristics give us:

$$Vm = km.w + I.Rm$$

$$I = Mi / km$$

where
km = Motor torque constant
w = Motor speed
Rm = Motor resistance
Mi = Motor torque

Combining these equations and putting km x km = (km)2, we write:

$$w = V0/km + Mi.(K/(km)^2 - Rm/(km)^2)$$

or if we put w0 for the speed at zero torque:

$$w = w0 + Mi.(K/(km)^2 - Rm/(km)^2)$$

Speed will therefore be constant if the feedback parameter K is made equal to Rm. In practice however it is not quite so simple, since the motor resistance is dependent on load and temperature.

Digital circuitry

The address bus from the backplane connector is decoded uniquely for the particular board. The initial prototype board used an EPROM for this decoding, but on the etched board this was performed by a Programmable Array Logic (PAL) chip. Initially the data bus was buffered, but this was not considered necessary for the final boards. Mechanical relays swap the motor connections to change the direction, and short the motor connections to provide an electromagnetic braking effect. The speed value from the data bus is fed into a D-A convertor, which provides the input to the analogue motor control circuitry. Two speed modes may be selected, effectively changing the reference voltage on the D-A. Both modes may be independently adjusted for speed range, in conjunction with the zero speed setting described below.

The optical encoders on the robot joints send back positive and negative directional pulses. These are summed on the motor control card and may be read by the EuroBEEB processor.

Analogue circuitry

The details of the analogue circuitry are shown in Figure 11.5. The main elements are the zero speed setting, the power amplification, the current feedback, and the current limit.

The zero speed setting is set by Vr1 at the input to the voltage amplification stage IC1a. IC1b is a summing amplifier, combining the voltage signal with the fed back motor current.

The power amplification is provided by transistors Tr1, Tr2, Tr3. The motor voltage is effectively set by the resistor chain R3, R4 multiplying the voltage at the emitter of Tr1, which is approximately equal to the input base voltage. Motor current is provided through the power transistors Tr2 and Tr3 in a Darlington pair arrangement. Instantaneous current limiting is provided by R26 and D1, D2 [65]. Diode D2 compensates for the base-emitter voltage drop of Tr2, and so the voltage across R26 is equal to the voltage across D1, which cannot exceed 0.6V. Thus the motor current is limited to 0.6/R26. This limit was not originally included on the prototype, but was added to protect the motor drive trains from too high a torque.

Current feedback is provided by taking the voltage across the series resistor to earth, R6, fed back through R2. This is fine-tuned by Vr2 to give the correct current feedback balance.

The point at which the current limit trips is set by Vr3. Originally the current limit acted instantaneously, for as long as the over current condition remained. On the final board however a delay is incorporated before the current limit trips out. The limit trip condition is latched until reset in software. The limit trip delay is set by Vr4. The state of the current limit is read at the output of the latch IC3. The latch may be cleared to reset the current limit. The current limit trip acts on the motor drive circuit by turning off IC1b.

The state of the current limit is indicated by an LED on the front panel. LEDs also indicate power supply status and brake status. The variable resistors for the Zero, High and Low speed settings, and for the current limit trip are also accessible on the front panel.

Evaluation

The current feedback method of speed control was chosen for cheapness and simplicity, but has not proved entirely satisfactory in practice. Ideally zero speed and speed range settings could be adjusted to give a precise numerical relationship between speed value specified in software and actual motor speed. This is far from the situation in practice, and precise speed control has been implemented in software as described later, although the resolution of the encoder is not appropriate for this to be entirely effective. It has proved extremely difficult to set up accurately the feedback parameters and, as mentioned above, the parameters themselves may change with load and motor temperature. It was not possible to adjust the zero speed setting to guarantee zero speed. In practice this was compensated for in software as described in the next chapter.

The use of mechanical relays for brake and direction change proved a major problem. The finite changeover time allows the back emf produced by the motor when braked to be fed back onto the power supply. This was a particular problem for the vertical actuator, which produces a significant back emf when stopped, causing the microprocessor to crash on occasions. This was eventually overcome by ensuring that the relays did not change while the motor was moving.

The op-amp IC1 on the board proved susceptible to failure. This caused either all speed control to be lost or the current limit trip to latch on. This was cured by replacing the original IC with CMOS input to an alternative device with bipolar input.

On the vertical actuator problems were also encountered with the drive transistor Tr2 blowing. This was cured by uprating the device.

POWER CONTROL UNIT

The power control unit, housed in a screened metal box, performs five main functions, in conjunction with the parallel user port (set to output) of the EuroBEEB.

a) Latch on the mains power supply when either user switch is pressed

b) Turn off the mains power supply

c) Turn on/off the robot 24v psu

d) Turn on/off the user interface microcomputer mains bus

e) Route the user switches to the user microcomputer

The operation of the power control unit is shown in Figure 11.6

Control of the mains on/off relay is performed through a 4013 D type flip-flop. The D input of the flip-flop is always held high. Initially the CK input is low. When either switch is closed the transistor is turned off, the clock input goes high and the high value on the D input is transferred to the Q output. This turns the mains control relay on. Sending the PB7 output high, causes the flip flop to reset. This sets the Q output low and turns off the mains control relay. On power on, the software must immediately set the User Port to output, with PB7 low, or the flip flop will be reset and turn the system off.

The other functions are simple actuations of 12v relays, through transistor switches, from the user port lines. For the mains relays, both Live and Neutral are switched. The mains relays are located within the PCU box, as is the relay to route the user switches. The relay for the robot 24v psu is inside the PSU box, and is accessed via a 3.5mm jack socket.

POWER SUPPLIES

Power supplies are housed in a screened metal box. The mains input comes from the power control unit. Three transformer rectifier circuits (Figure 11.7) produce 8v(5A), 24v(6A) and 24v(1.5A). The 24v supplies are for the motors of the arm and are unregulated. The 6A supply (limited to 2A to limit the motor torque and thus protect the gearhead) is for the vertical actuator and the 1.5A supply for the other motors and the mains control relays. The 24v supplies are switched on or off by a relay, driven from the power control unit. Before the switch, on the 1.5A supply, an auxiliary supply is taken off to power the mains control relays (these should operate irrespective of whether the arm supply is on). The 8v supply is regulated and provides power supply to the processor card, motor control cards and arm sensors.

The 24v 1.5A supply is connected to the rack backplane through the power/buffer card (Figure 11.8). The 8v supply also is fed onto the power/buffer card. There is a through connection to the backplane for the motor control cards and sensor interface card. The 8v is also regulated further to 5v to give a 1A supply for the arm power rail and to a 2A supply for the EuroBEEB processor. The power buffer card also provides buffering for the address, control and data buses.

The 24v 6A supply is supplied direct to the vertical actuator motor control card, through 4mm connectors on the front panel of the card. The 24v 1.5A auxiliary supply is taken direct to the sensor interface card.

The 8v supply for the motor control cards and sensor interface card is regulated to 5v 1A on each of the cards.

Provision of power supply to the various units is summarised below:

24v 6A (unreg) to vertical actuator control card (2A current trip)
24v 1.5A (unreg) to arm motor control cards, through power/buffer card and also to power mains control relays.
8v 5A (reg) to power/buffer card provides:

- 8v to motor control cards (regulated to 5v on each card)
- 5v 1A to arm
- 5v 2A to EuroBEEB

12v 1A (reg) in Power Control Unit to PCU interface board, and infra-red switch receiver unit.

SENSOR INTERFACE AND MAINS CONTROL CARD

Mains control relays

The control bits for the controlled mains outputs are buffered on the card and fed to an IDC male connector on the front panel. The data is latched by a line from the PLS173 PAL chip (see below). A ribbon cable takes the control signals to the relays mounted near the sockets on the back panel of the cabinet. Originally 10A mechanical relays were used because of their low cost, but problems were encountered with switch bounce causing power supply disturbances to the EuroBEEB computer. The relays on sockets 1 and 2 were replaced with 2A solid state relays and on socket 3 with a 7A solid state relay. Sockets 4-7 are no longer used. The final control bit from the buffer was used to control the open/close operation of the Hugh Steeper gripper when it was fitted.

Sensor status

The IR sensors on the arm are read using a single A-D converter. The circuit is illustrated in Figure 11.9. The ADC 0809 device is an 8 bit converter, with up to 8 inputs selectable by a 3 bit code. The chip runs at 1 MHz (obtained by halving the 2MHz clock pulse on the bus) giving a conversion time of 60 microseconds. The address bus is decoded by a PAL chip. All the LEDs are turned on by a single code. The sensor to be read is selected by a 3 bit code on the A-D chip, latched in by the address latch enable (ALE) line.

Single data bits trigger the A-D conversion (START) and monitor the end of conversion (EOC). The output value is read on the data bus, latched by the output enable (OE) line.

The state of the arm microswitches is monitored. At a later date the shoulder microswitch, unused in practice, was replaced by the tape switch below the wrist. The card also includes line termination resistors for the backplane bus.

INFRA RED TRANSMITTER RECEIVER

The infra-red transmitter/receiver utilises the same components as that used in the Atlas system. It uses coded Pulse Position Modulation (PPM) signals. Standard ICs are used as described in the RS Data sheet 7786. The block diagram for the system is given in Figure 11.10.

Transmitter

The transmitter unit has a 7 pin din socket into which may be plugged either a single or double user switch. The transmitter IC RS490 is a PPM transmitter with a 5 bit word, driving the IR LEDs directly. The switches are connected directly to the IC to turn on or off bits 2 and 3 of the signal.

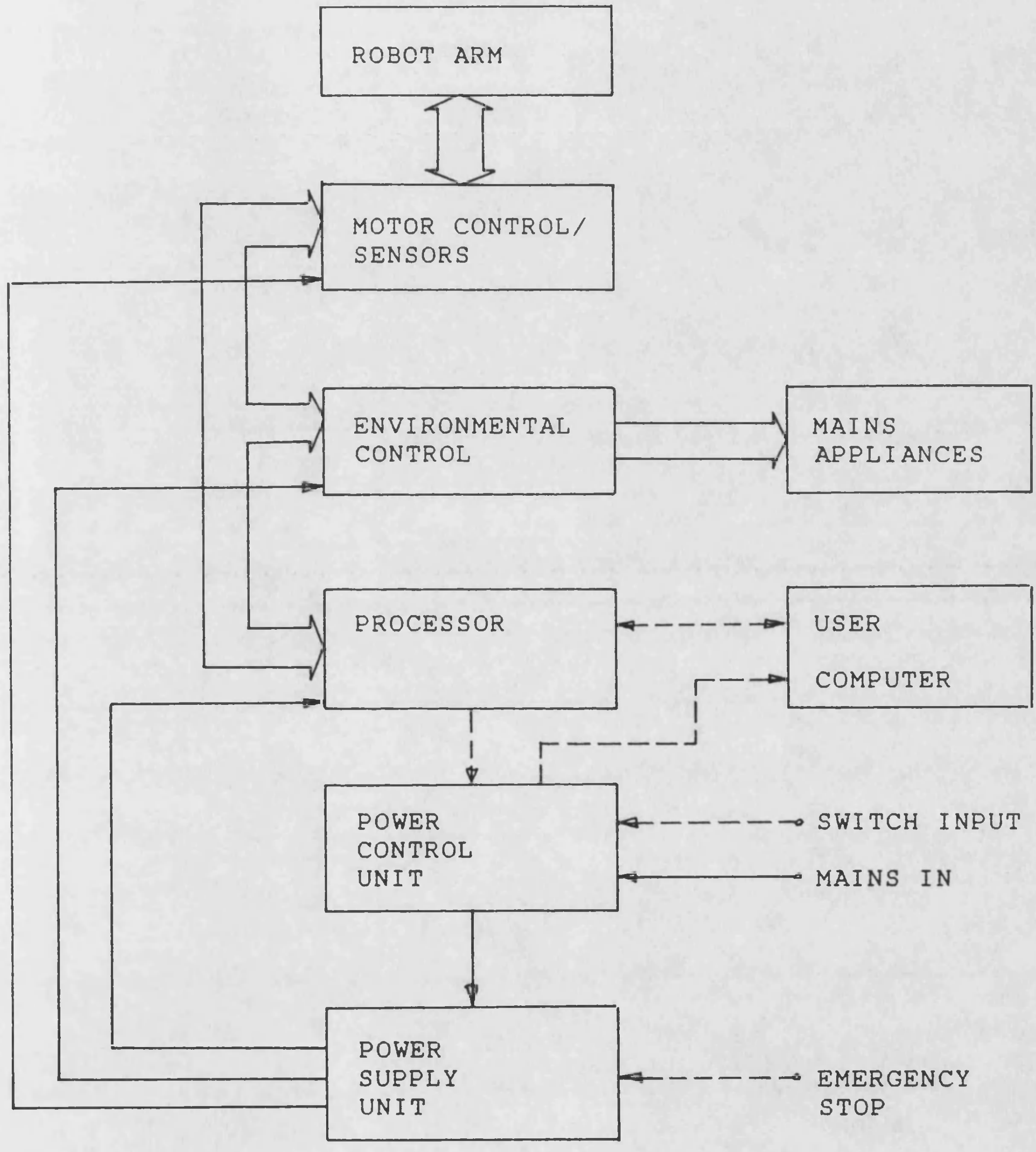
Receiver

The pre-amplifier RS486 is a high gain pre-amplifier forming an interface between the IR receiving diode and the digital input of the receiving circuit. The RS926 decoder takes the PPM signal and decodes it to four binary outputs. Bits 2 and 3 of the output turn on and off the transistors which are seen as a switch input by the user micro or PCU dependent on the position of the rotary switch. The switch has three positions to give IR input, directly connected switch input, or both in parallel.

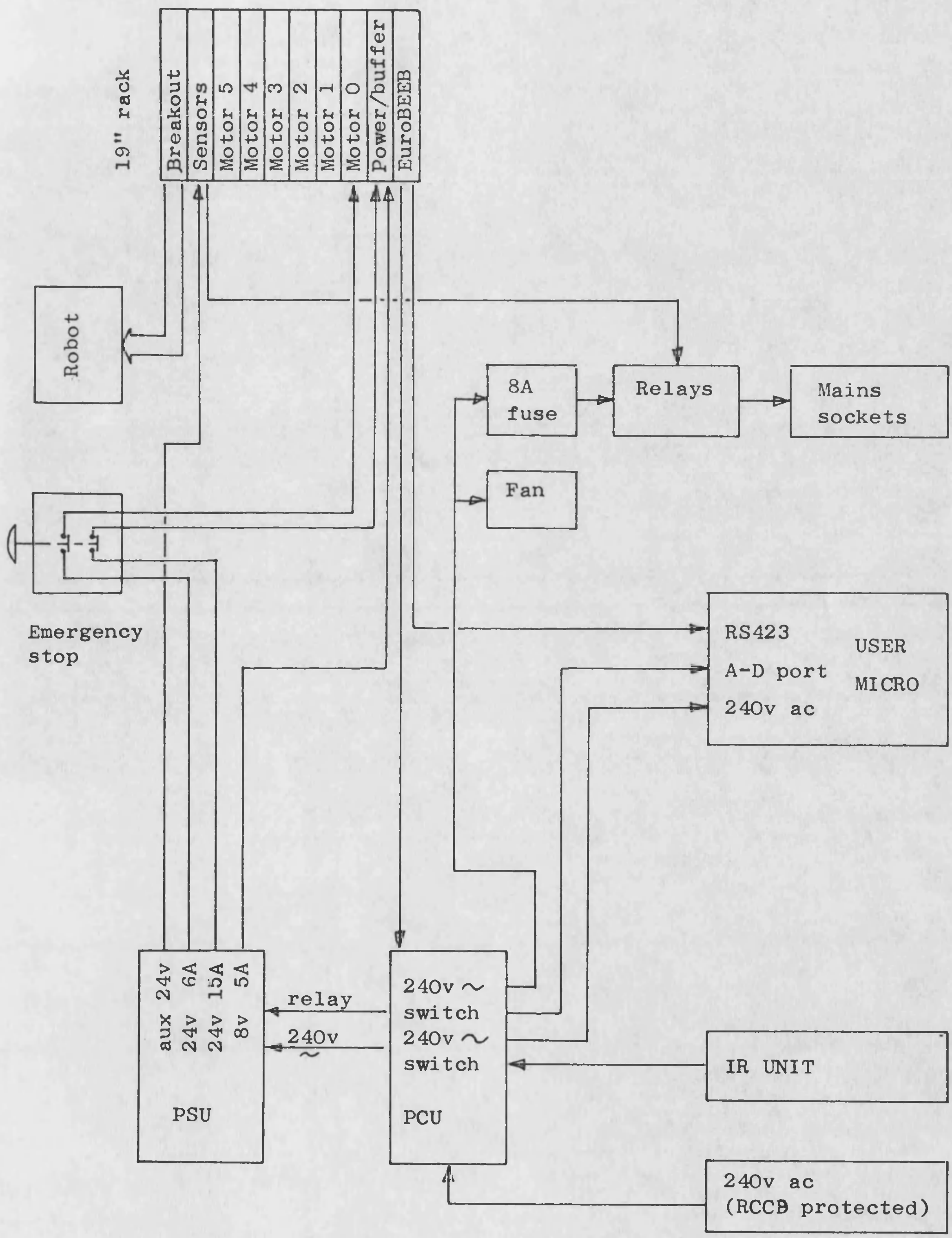
EUROBEEB I/O MEMORY MAP

Location	Function	Bytes per motor (etc)	R/W
&FE00	Power control	b2=Route user switches	R/W
		b5=Robot 24V PSU	
		b6=User microcomputer	
		b7=System off/on	
&FE40-&FE4B	Counter bytes	2	Read
&FE4F	Load counter bytes to latches		Write
&FE50-&FE55	Counter reset	1	Write
&FE57	Motor limit status	1 bit	Read
&FE58-&FE5D	Current limit reset	1	Write
&FE60-&FE65	Speed value latch	1	Write
&FE68-&FE6D	Control latches	1 b0=Direction	Write
		b1=Brake	
		b2=Speed mode	
&FE70	IR sensor	b0=Emitter LED on/off	Write
		b1-3=Select sensor	
&FE71	Start A-D conversion		Write
&FE72	Result of A-D	b0-6=Result	Read
		b7=End of conversion	
&FE73	Microswitch status	b5=Vertical	Read
		b6=Shoulder	
		b7=Roll	
&FE75	Mains sockets	b0-6=Mains relays	Write
		b7=Hugh Steeper gripper	

Table 11.1



Wolfson Workstation - Electrical functional diagram Fig. 11.1



Electrical system - block diagram and interconnections Fig. 11.2

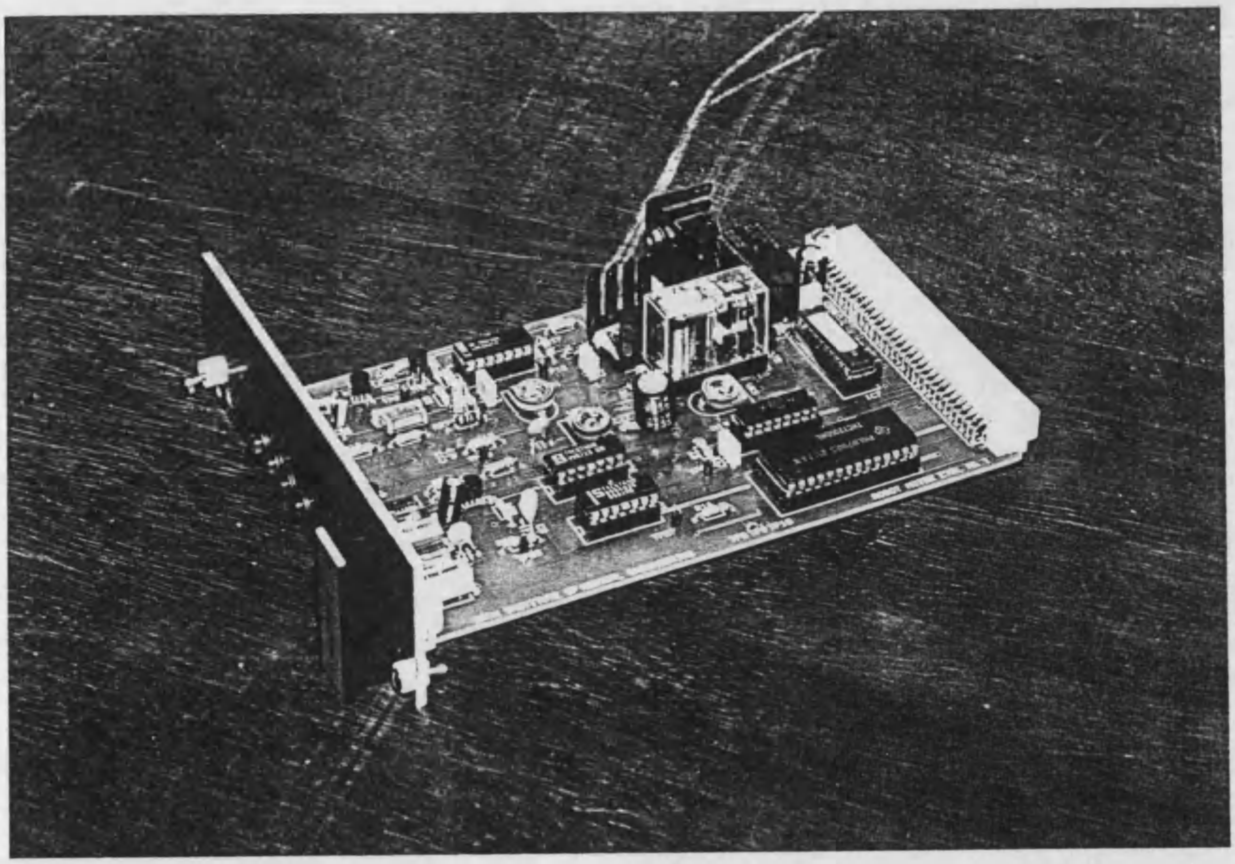
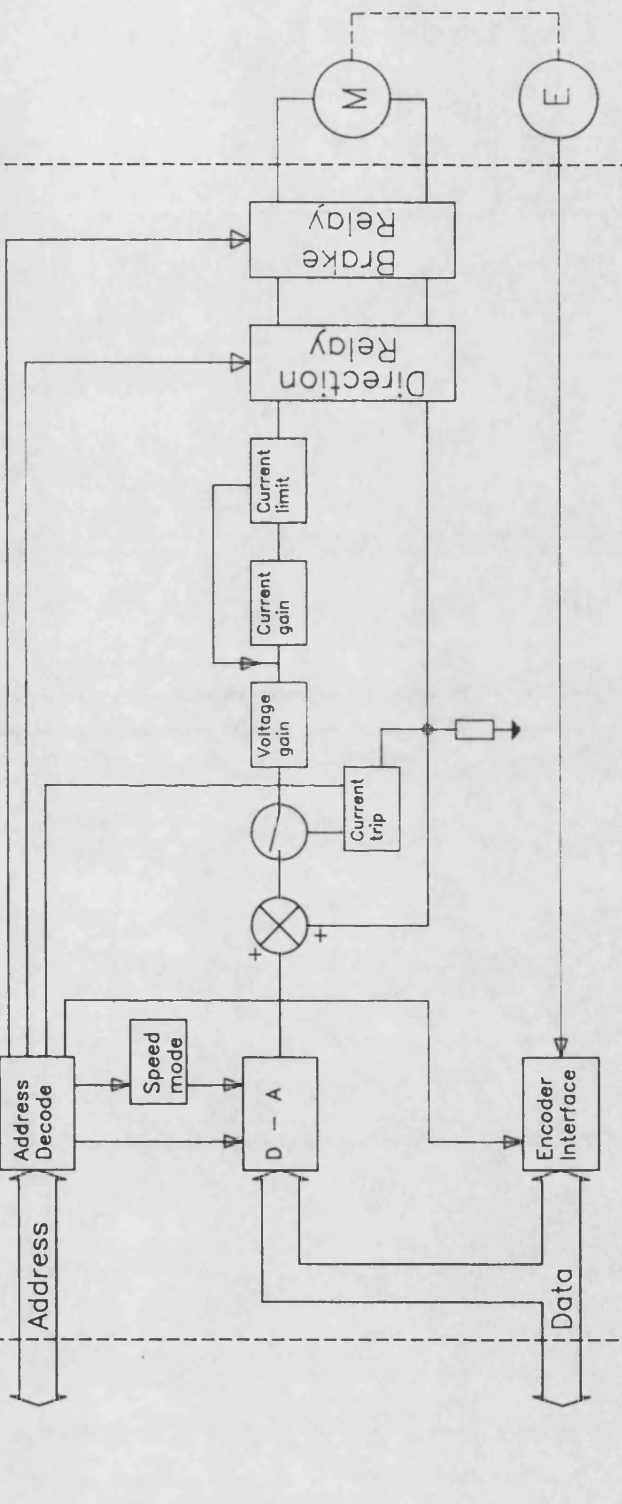
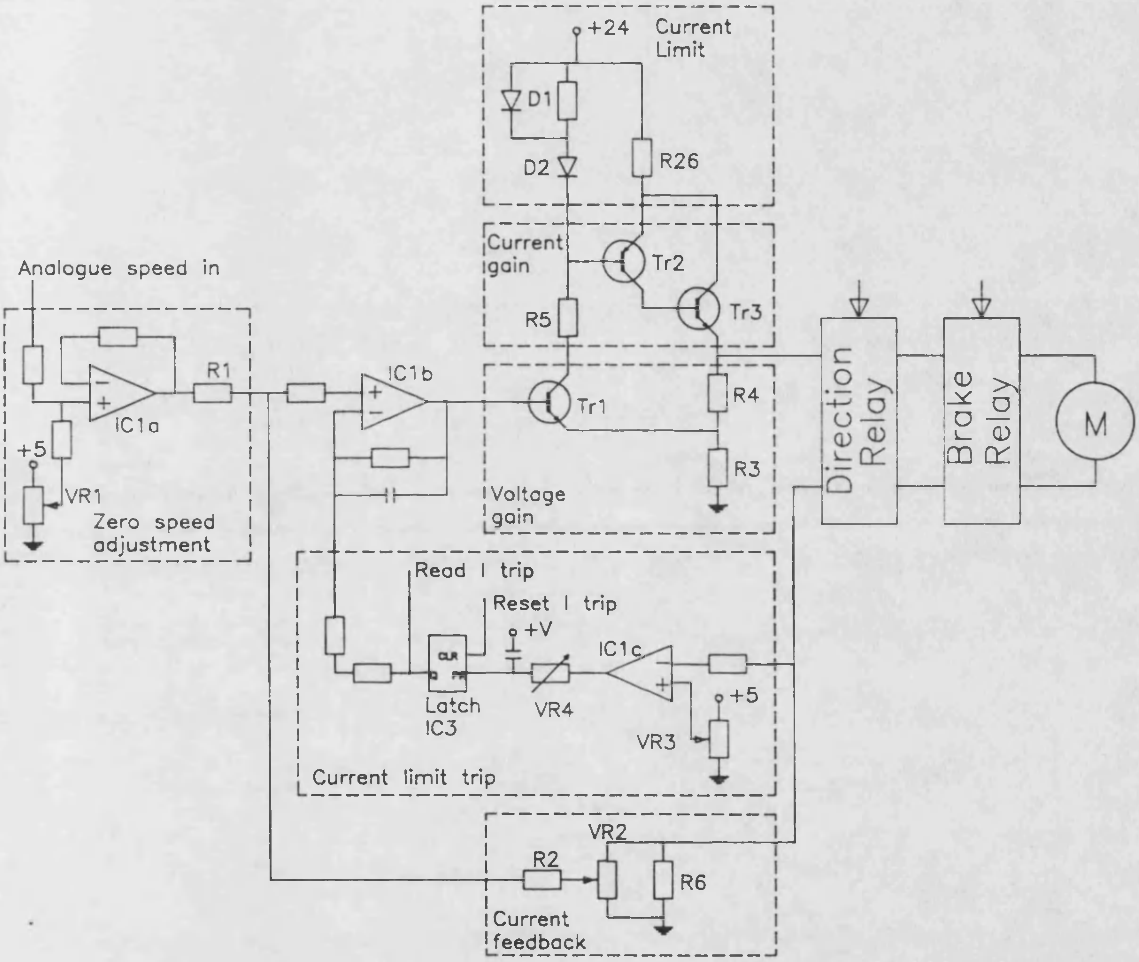


Photo of motor control board Fig. 11.3



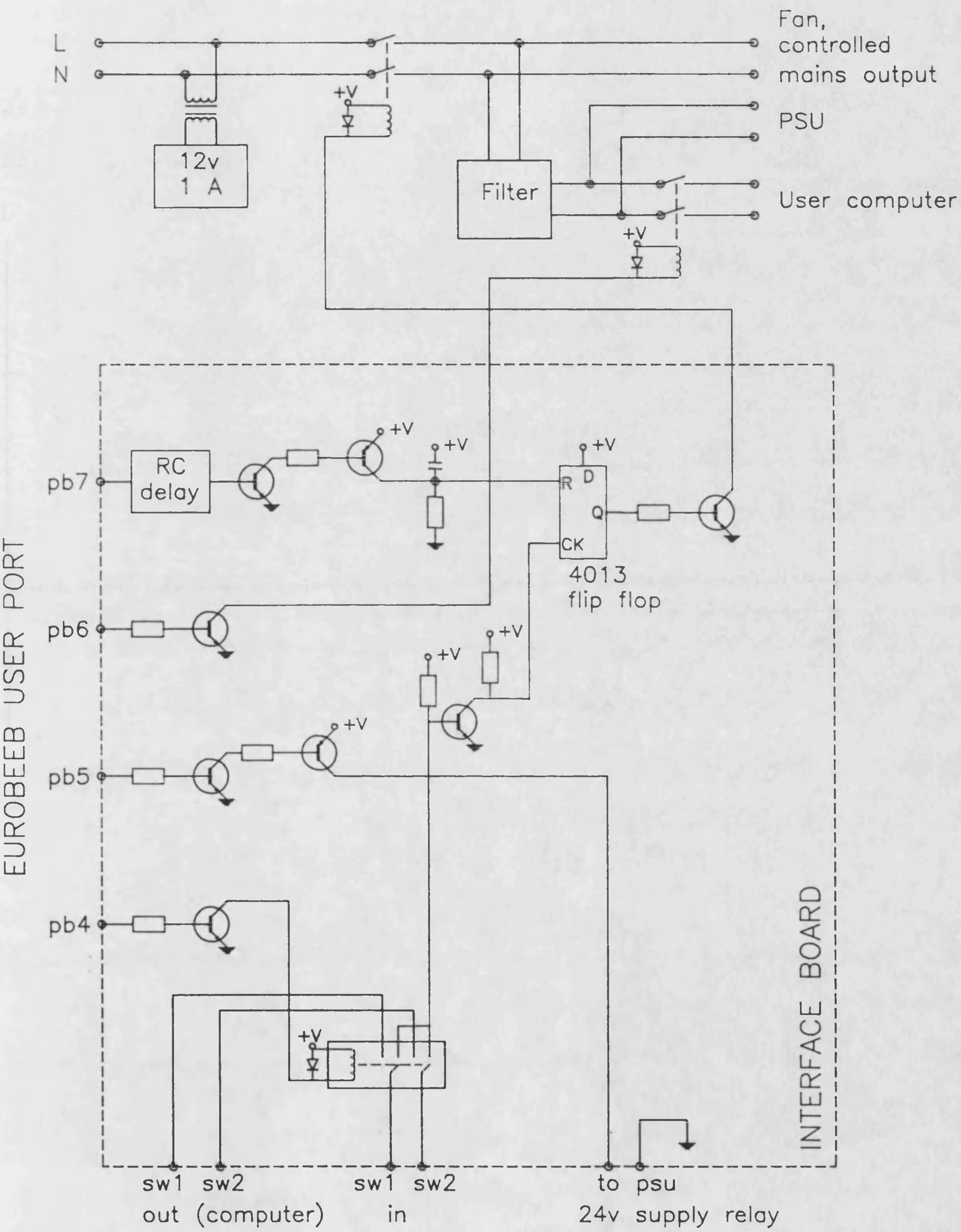
Motor control - Block diagram

Fig. 11.4



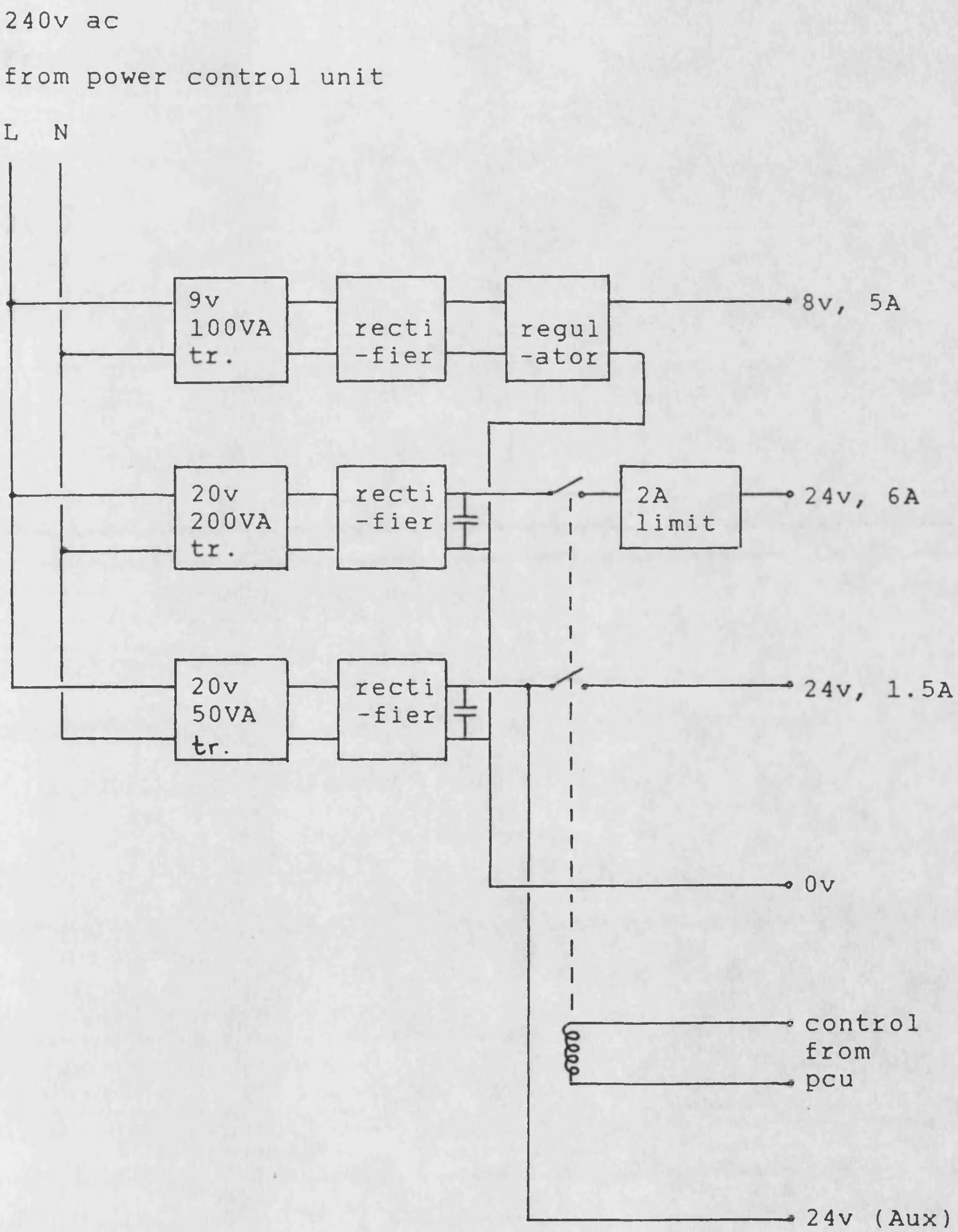
Motor control – Analogue circuitry

Fig. 11.5



Power Control Unit

Fig. 11.6

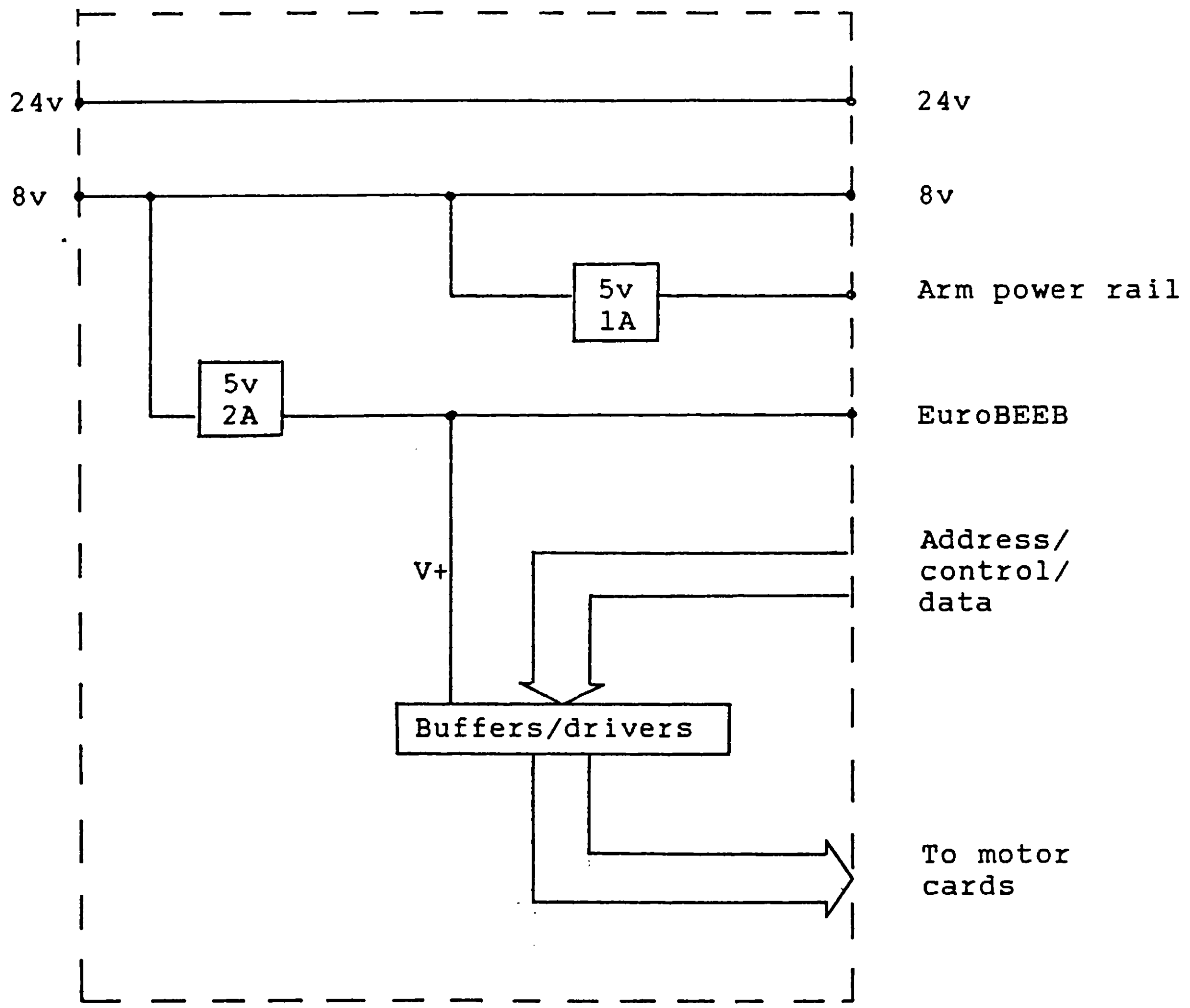


Power supply unit

Fig. 11.7

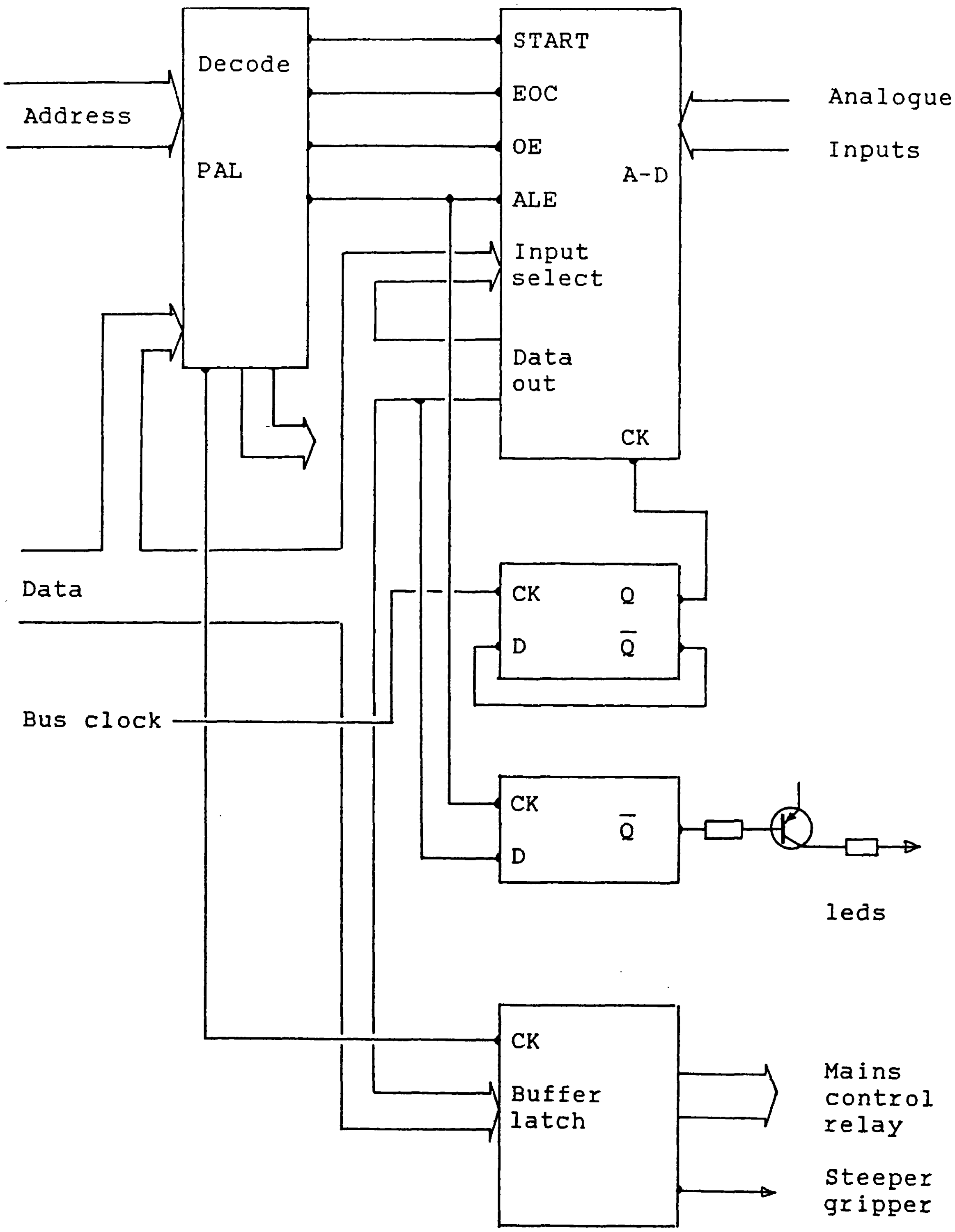
Front panel

Rear backplane



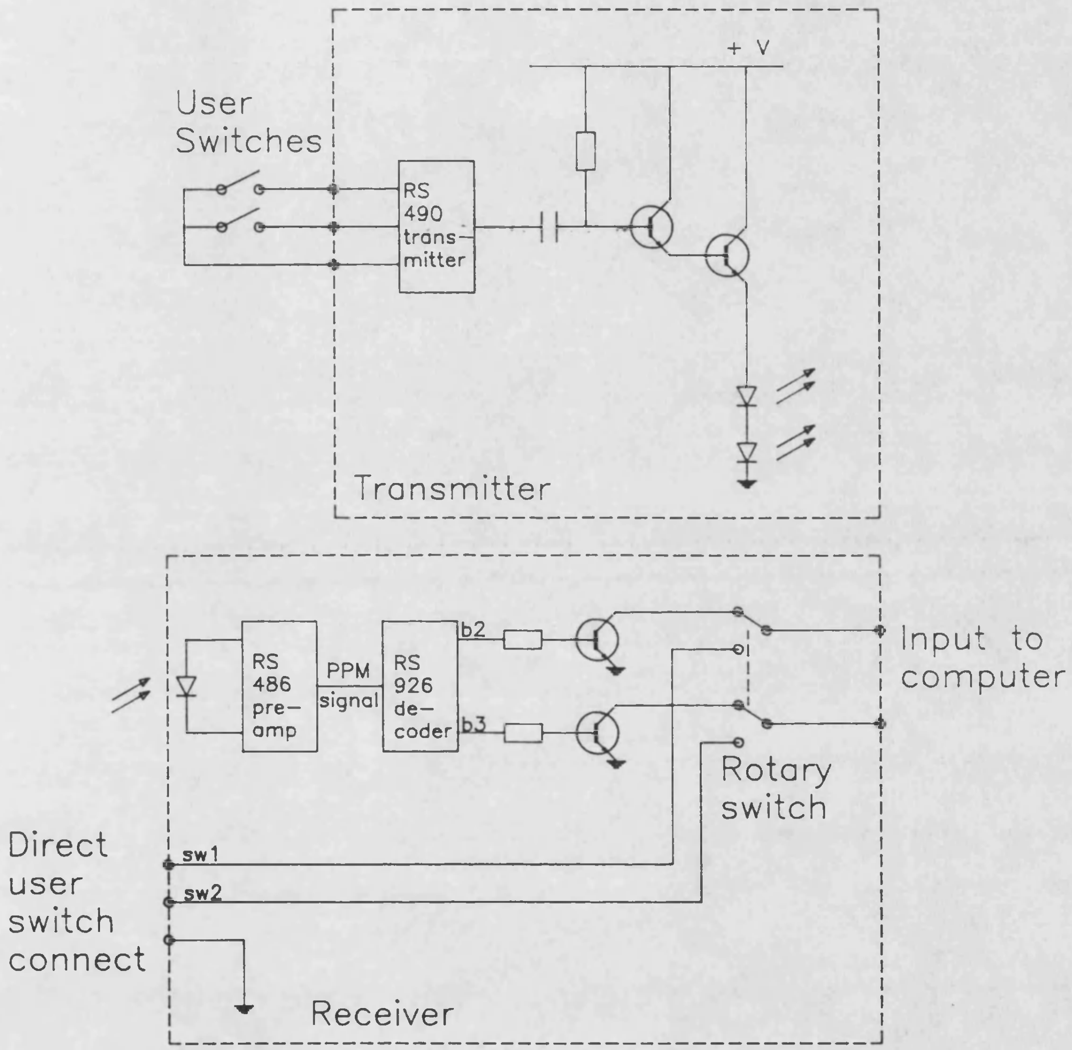
Power, buffer card

Fig. 11.8



Sensor Interface and Mains Control Card

Fig. 11.9



Infra-red transmitter / receiver

Fig. 11.10

Chapter 12. WOLFSON WORKSTATION SYSTEM - SOFTWARE

INTRODUCTION

The software is in two distinct parts. The user interface software was implemented on a BBC Microcomputer, and the robot control software on the EuroBEEB card. The interface software communicates with the control software via a serial link.

The control software is able to control the robot either under the direct control of the user, or as the replay of a preprogrammed routine. A major function of the control software provides an algorithm for straight line movement. The control software also includes facilities for handling and editting of the preprogrammed routines.

The user interface is based around a scanning menu based system. A variety of switch inputs may be used. The options, selected from various menus, call the different options provided in the control software. Two different menu structures have been programmed for beginners and more advanced users of the system.

COMMUNICATION PROTOCOL

The user interface software was implemented on a BBC Microcomputer, and the robot control software on the EuroBEEB card. The two systems communicate via an RS423 serial link at the default baud rate of 9600. A communication protocol was written to check for errors and to act as a watchdog system. The protocol is illustrated in Figure 12.1. Initially the EuroBEEB waits to receive a code "01" from the interface system. On receiving the correct code it replies with code "00". The interface then sends an opcode, followed by a block of data. The EuroBEEB confirms with code "02" when the data has been received. The interface system waits while the operation is carried out, till a code "03" is received. The EuroBEEB sends a block of data to the interface, which replies with code "02" when it has been received. Error codes are sent if an incorrect code is received, or if a timeout error occurs.

If the operation involves movement of the arm, then the EuroBEEB constantly requests a continuity signal from the interface as a safety watchdog. Every 10 centiseconds the EuroBEEB sends a code "20". The interface system replies with a continuity code of "17". If this is not received by the EuroBEEB within 10 centiseconds then the arm movement is halted. Other valid codes which may be received by the EuroBEEB are "16" to start the motion, "18" to stop and "19" to end the operation.

If the interface receives an incorrect code or a timeout error occurs, then it will reset the EuroBEEB system by setting the receiver input high for approximately 1 second. This also has the effect of stopping any motion and turning off the controlled mains sockets. If the error is due to the RS423 lead being removed, then the reset signal will obviously not be received.

The opcodes used to communicate between the interface and the EuroBEEB are tabulated in Table 12.1.

EUROBEEB MOTOR CONTROL SOFTWARE

The EuroBEEB computer handles the robot control, operation of the controlled mains sockets and the storage and manipulation of routines. The software is coded in 6502 machine code. The code is written in 11 separate assembler programs on the BBC Microcomputer. Each program assembles relocatable code into memory &7000 - &7C00. This code is then downloaded from the BBC to the EuroBEEB. Each block of assembler code has an area of local memory, and may also access areas of shared variables.

Overall description of EuroBEEB software

A brief description of the operation of each of the assembler files follows.

CMAIN	Main program loop to communicate with the interface system. Also initialises the system after either a "power-on" or "warm" reset.
DIRECT	Operations as defined by opcodes &00 - &0F. These operations are mainly concerned with direct control of the robot or controlled mains sockets.
REPLAY	Operations as defined by opcodes &10 - &1F. These operations are mainly concerned with the control of the robot or controlled mains sockets by preprogrammed routines.

EDIT	Operations as defined by opcodes &20 - &2F. These operations are mainly concerned with the editting of preprogrammed routines.
ROUTLS	Operations as defined by opcodes &30 - &3F. These operations are mainly concerned with the loading, saving and manipulation of preprogrammed routines.
HOME	Concerned with the reset, parking and moving to "home" positions of the arm.
GRIPPER	Gripper functions.
MOTOR	Concerned with the controlled movement of all motors, either in straight line mode or single motor.
CALCXY	Forward and inverse kinematic calculations of the position of the robot wrist.
UTILM	Low level routines for operation of the motors, mains sockets, and poower control.
UTILA	Basic arithmetic and miscellaneous utility routines.

Reset

The position of the arm is monitored by incremental optical encoders. When the system is turned off power is lost to the encoders and therefore it is not possible to guarantee the precise position on power-on. It is therefore necessary to reset the position of the arm. This is done by driving the motors against either their mechanical endstops or a limit position switch. (Initially optical sensors were used to detect the edge of the arm to ascertain position, but this proved unreliable in bright sunlight, inspite of taking ambient conditions into account.) After zeroing the joints against the endstops in the order outlined below, each is moved to the park position and zeroed again.

* Move vertically up by 2" to ensure clear of desk top.
* Zero gripper by closing till current limit trips.
* Rotate wrist through 45 degrees to clear lower arm for roll etc.
* Zero roll against internal microswitch
* Zero wrist against mechanical endstop till current limit trips
* Zero elbow against mechanical endstop till current limit trips
* Zero vertical actuator against internal microswitch
* Zero shoulder against mechanical endstop till current limit trips

There are possible starting positions of the arm for which the above procedure will cause the arm to collide with itself (eg wrist against the vertical post) or the environment. Our approach to this has been to allow the user to interrupt the reset procedure, adjust the position of any joint, and then continue the reset.

On reset, a repeatibility of +/- 0.1mm was obtained on the vertical actuator, and a repeatibility of +/- 0.16mm was obtained for the shouder (measured at a radius of 12").

<u>Park and Home</u>

The park position is defined with the arm folded on top of itself to the right of the desk. In addition various temporary "home" positions may be defined by the user. If the gripper is holding an object it will not park until the object is released by the user.

<u>Gripper</u>

The gripper routine is entered with the following codes.

0 = Grip (to maximum force, ie current limit trips.)
1 = Release
2 = Move gripper to specified opening
3 = Gripper to home state
4 = Reset gripper counters
5 = Direct control of the gripper opening
&FF = Read gripper state

Movement Control

Single motor control uses a ramped speed profile. The ramp up is proportional to time, up to the specified speed. For replay control the ramp down is proportional to distance to the target position. This does not give a linear ramp down of speed, but avoided the use of a more complex arithmetic function. Target position is defined as having been achieved when the position counter is just at or past the target position. Although this may cause a certain amount of overshoot, in practice this can be eliminated by careful tuning of the ramp down parameter. Once the position has been achieved the brake is put on. There is not constant position control, but the system relies on the stable geometry, internal friction and the electromagnetic braking effect to maintain position.

Accurate control of the speed cannot rely simply on the current feedback (IxR) speed control electronics. Further control of the speed is performed in a clock driven interrupt routine. A simple speed correction factor is applied.

Motor signal = Motor signal x Factor x (Required speed - Actual speed)

The speed is defined as the number of encoder pulses in a four centisecond period. Due to the encoder being mounted towards the output end of the drive train, the resolution of speed was poor.

Zero speed is difficult to set up on the electronics card, since the zero speed setting point will vary with the friction at different rotational angles and direction of motion of the joint. This is overcome in software by manually setting zero speed on the card with the motor signal at a non zero value. Zero signal is therefore guaranteed to give zero speed. For a non zero speed, the motor signal is offset by the required amount as initially set up, and will then home-in on the required speed due to the action of the correction factor.

Tuning of the motor is by adjusting current feedback and zero speed on the electronics card and in software by varying the proportional constants for ramp up and down, the zero speed signal offset and the speed feedback factor. Speed profiles for a typical motor before and after tuning are shown in Figure 12.2.

The interrupt routine also performs various checks.

* End position (defined just before mechanical endstop is reached). The end position may be modified for various arm configurations to avoid self-collision.
* Check whether movement has stopped after zero speed has been requested.
* Check for motor "runaway" condition, defined as speed higher than an allowable value when zero speed is requested. This was incorporated to detect an error in the motor control electronics.
* Check state of current limit trips.

Straight line movement

For easy control of a robot by a user in real time it is vital to have straight line motion, rather than requiring the user to move individual joints. The manipulator may be controlled to move in a straight line either along the axes of the desk top, or along the gripper axes. Only with a cartesian geometry can straight line motion be achieved simply. With the geometries of the Wolfson system robot (as for the Atlas) the straight line problem was simplified to allow easy coding with a relatively slow microprocessor. The problem was simplified to straight line motion in a horizontal plane, keeping the wrist at a constant orientation. Three motors must be controlled, being shoulder, elbow and wrist. Vertical motion is easily achieved with just one motor controlled.

The basic method used is to approximate the straight line motion to a series of moves between points a small increment apart. While the individual points are on a precise straight line, the path between the points is undefined. A further simplification is that it is the motion of the wrist (rather than the end of the gripper) which is actually controlled. The wrist actuator is simply controlled to keep the wrist orientation constant. Because of the finite time taken to calculate the required velocities for the different motors, the processor must always be calculating ahead, and the joint velocities are set to aim for a position ahead. The basic straight line algorithm is illustrated in Fig. 12.3.

With robot control one of the major problems is that of singularities. This is a geometric point at which one of the joint angles is not uniquely specified. The effect of this is that one or more of the joint velocities tends towards an infinite value. A physical analogy is of what happens when one is watching an aeroplane fly overhead. As it passes vertically above, the position of the head is temporarily undefined as one changes from looking forward to looking backward.

With the simplified control method we have used, singularities are not a problem. Since we are using quasi-positional control, rather than velocity control each geometric point has a uniquely defined set of joint positions. (In the case of the Wolfson geometry there are two solutions, but this is limited to one since the elbow is constrained to be between 0 and 180 degrees). The motion is not based on a constant spatial velocity but on keeping all the joint velocities below a certain maximum limit, and factoring other joint velocities appropriately. Thus rather than the possibility of one joint velocity tending to infinity, velocities of the other joints are factored and tend towards zero. This leads to an uneven spatial velocity, but in practice this has not caused any problems. Figure 12.4 illustrates spatial velocity and joint velocities for a typical straight line trajectory.

The basic Denavit Hartenberg matrices are derived in Appendix 1. From these may be derived the forward kinematic equations for the system. Manipulation of these equations gives the inverse kinematic equations.

Initially a pair of two dimensional look-up tables was used for the inverse kinematics. This method did not prove satisfactory due to the interpolation error. Although the spatial error was acceptably low, in some configurations this lead to an unacceptably large angular error at the joints. The solution to this was to get nearer to a direct calculation of the joint angles, but using look-up tables for the angles formed between the links of the arm as a function of the square of the distance between shoulder and wrist, as shown in Appendix 1.

There are various sources of error in the straight line motion. The first of these is that the motion is based on specific incremental positions rather than a continuous straight line. For an increment of 0.5" the maximum error possible is only .03". The use of look up tables causes interpolation errors but these are negligible. The points in the table are not linearly spaced, but bunched to minimise interpolation errors. A further and more significant error source is that only a limited number of integer speed values may be specified. If we assume a maximum speed of 25 speed units (defined above as the number of encoder pulses in a 4 centisecond period) for one motor, then there is a maximum possible error of 4% for each of the other two motors. This leads to a maximum position error of approximately .04" over a 0.5" increment. Another source of error which is more difficult to predict or measure is due to the nature of the speed control algorithm, particularly on start up. The initial ramp up of speeds may cause one motor to initially advance more than the others. The error may be reduced by using a slow ramp up.

None of these errors are cumulative and the motion homes into the correct trajectory. From a practical point of view the wobble at the end effector has been observed to be approximately 0.25".

Environmental control

The system has seven controlled mains sockets (later decreased to only three) and these may be turned on or off. There is also the provision to associate name labels with each of the sockets, and these are stored in a block of memory on the EuroBEEB

Routines

A series of movements, as controlled directly by the user may be saved for future replay. Preprogrammed routines are defined by the use of various opcodes as given in Table 12.2. The start of a routine is defined by the user specifying either "park" or "set home position". Thereafter all motor movements are recorded as relative movements either of an individual motor or of all motors (usually after a straight line movement command). For replay, the series of motions may be repeated exactly as initially performed or may be editted by the user. If the routine is editted, extra lines may be incorporated such as introducing a loop into the routine or the addition of a pause.

During replay the motion may be stopped by the user and the position adjusted. If the current opcode being carried out is for absolute movement the arm will move from the new current position to the specified absolute position. If the opcode is for a relative motion then the relative motion will be continued from the new current position. Thereafter the motion will be offset from the original position until an absolute movement opcode is encountered. A line may be incorporated into the routine so that an adjustment of the position is specifically prompted for.

Up to 36 preprogrammed routines may be stored. The maximum number of 36 is defined by the catalogue system which has six directories, each with space for six routines. The routines are stored in a compressed form. For creation or replay of routines they are tranferred into two memory blocks in an expanded form which is easier to manipulate and edit. Details of the routines may be read, written or editted by the interface system. The handling of routines is in concept very similar to that used for the Atlas systems.

Memory allocation

The EuroBEEB addresses 64k of memory. Usable battery backed RAM is from &E00 up to &7FFF, though blocks of this may be redefined as ROM/EPROM. Paged ROMs, including BBC Basic are from &8000 to &BFFF, with the operating system from &C000 to &FDFF, and externally addressable memory from &FE00 to &FEFF

The use of this memory space is given in Table 12.3. As can be seen the program (and look up table) occupies &4000 to &7FFF. This has been put on an EPROM. At a later date this may be transferred to &8000 to &BFFF to act as a language ROM, and allow more memory space for routine storage.

USER INTERFACE SOFTWARE

The User Interface Software is implemented on the BBC Microcomputer, and the basic appearance is very similar to that used in the earlier system. The interface resides in battery backed sideways RAM. This arrangement means that the computer powers up into the interface software. Battery backed sideways RAM is used, rather than an EPROM, in order that the interface should be easily modified for different users.

The software is coded in 6502 machine code. The code is written in 8 separate assembler programs on the BBC Microcomputer. Each program assembles code into sideways RAM from &8000 - &BFFF. Each block of assembler code has an area of local memory, and may also access areas of shared variables. The memory usage is given in Table 12.4.

Overall description of Interface Software.

A brief description of the operation of each of the assembler files follows.

HEADER	Set up the ROM header so that the interface code acts as a paged ROM.
MAIN	Sets up the overall menu structure for the interface
MENUS	Defines the action of the menus for direct control, use of the environmental control, and the loading and saving of routines
EDIT	Code for the display and manipulation of routines using the editting facilities
SCREENS	Procedures for the basic handling and screen display of the menus.
SWITCH	Handles setting up of switch options, the action of input switches, and also the communication with the EuroBEEB.
ERROR	Displays error messages and screen prompts.
UTILITY	Low level utility routines, especially for screen display

Menu Structures.

The menu structure is defined in the assembler file MAIN, by means of data statements. The format is as follows.

- Start line number (1 byte)
- No of options (1 byte)
- Spacing of menu lines (single or double height) (1 byte)
- Heading text (1 byte = no. of characters, plus text string)
- Text for each option (as heading text)
- Pointer to start of code for each option (2 bytes)

The code for each option returns values in the A and Y registers, to determine the subsequent action.

- A=0 : remain in menu
- A=1 : quit menu
- Y=&FF : scan from top of menu
- Y=+ve : select option Y

Since it is easy to change the menu tree structure by modifying and then reassembling the file MAIN, various arrangements have been used. Two structures however have been particularly used. The first, illustrated in Figure 12.5a provides all the functions, with two sub-menus for Direct control and Replay control. The second, illustrated in Figure 12.5b is intended for those who are new to using the system and only provides the more important functions. The initial screens for each are shown in Figs. 12.6 (a) and (b) respectively.

Functions available

The functions available are split into a number of main types, direct control of the manipulator, control through replay of routines, environmental control, system control and help messages.

There are three modes by which the manipulator may be controlled directly. For the SCARA type geometry, vertical motion requires only a single motor, while movement in the horizontal plane requires three motors. The relative control of the motors is performed in the EuroBEEB computer, so that the user is concerned only with commands for forward/backward/left/right. The movement control menu therefore has the following movement commands:

Up/Down
Forward/Backward
Left/Right
Wrist yaw anticlockwise/clockwise
Wrist roll clockwise/anti clockwise
Gripper close/open.

The screen display for direct control mode is shown in Fig. 12.7.

The horizontal movements are basically defined relative to the edges of the desktop. A variation on this, which experience with both able bodied and disabled users has proved to be preferable, is to define the horizontal movements relative to the direction of the gripper. This is referred to as "Pilot" mode. The third option allows control over the individual horizontal joints independently.

Other commands which give direct control of the arm are to return to the parked position at the front of the desk or to the current "home" position. The "home" position may be set up by moving to any required position, and commanding that that position be defined as the current "home".

When under direct control the sequence of movements is saved in the EuroBEEB computer and if required may then be replayed or stored as a routine for future replay. Obviously the start of a sequence of movements must be marked. This is done by selecting the "park" or "set home" commands. Selection of either of these clears the memory space in EuroBEEB used for temporary storage of routines.

Routines stored for future recall and use are stored under six directory headings. On selecting functions such as "load", "replay" (ie load + run) or "store" the user is presented with six directory headings. Selecting one of these presents a list of up to six routines which may be selected. When a routine is being replayed the user may at any moment interrupt the movement, or the "adjust" or "loop" opcodes may return control to the user. He is then presented with a menu of various options, depending on the condition which caused control to return to the user. The return functions are to adjust the position of the arm, to simply return to the routine or to return to the routine but skipping the remainder of the current motion. If the routine is within a loop the return function may be to repeat the loop or exit the loop. Alternatively the return function may be to return to the start of the routine or quit the routine. After adjustment of the motion the trajectory of the manipulator is offset by the amount of the adjustment until an absolute position command is encountered.

This feature is valuable for situations where an object is slightly away from its expected position, allowing the gripper position to be adjusted. As well as incorrectly positioned objects this feature may also be used deliberately to select one of a range of objects from a rack. The preprogrammed routine will bring the gripper to a position in front of the rack, the user will interrupted the movement and manually scan across the rack, and then the preprogrammed routine will continue the gripping and manipulation of the object.

Routines may be editted. The screen display is illustrated in Fig. 12.8. The editting options available are different from those available in the earlier system and are as follows:

SCAN DOWN. Move the cursor to the routine listing and scan down.

SCAN UP. Move the cursor to the routine listing and scan up.

DELETE. Delete the line currently pointed to.

ABS/REL. Swap between absolute position and relative movements where appropriate.

MERGE. When a routine is created there will obviously be a certain degree of back and forward movement to home in on a position. Also movement to a position will normally involve movements in several orthogonal directions. It is therefore possible to edit out these unwanted movements, and merge the motion to move straight to the required position in a single movement.

There is an environmental control facility which allows each of the controlled mains sockets to be turned on or off. The screen display is as illustrated in Figure 12.9. Initially each socket is described as "spare". However simply typing text at the keyboard, with the cursor on the relevant line, will provide a name for the device in each socket. These titles are retained in the EuroBEEB system memory. Another facility is to turn off the whole system.

Since the computer may also be used for other applications another function is to exit the interface software. In some instances use of the computer is not required by the disabled user (and so is not in the menu structure). However access to the computer will be required for software development and debugging; in these cases pushing "B" and the Break key on the computer will enter the computer in its "Basic" mode. This function is defined as a service call in the header of the interface S-RAM.

A facility added subsequently is to provide help messages. These outline the basic purpose and method of operation of the system. The text currently occupies 4 kbytes of memory. At a later date it should be rearranged so that the text (in a fuller form) is stored on a separate EPROM.

On the first occasion on which any of the functions are selected (except environmental control) the reset procedure of the arm is carried out. Starting from near the parked position there is no problem with the arm clashing against itself or the environment. However if reseting from a more obscure position, if the user fears a collision, he may interrupt the reset procedure and move the motor joints to a more favourable position.

Various of the functions either initiate a movement (eg "park") or perform a function which is not easily reversed (eg "off") on a single switch press. This is undesirable from a safety point of view. Therefore for these functions the system prompts for another switch press to confirm. If there is not a switch press, the system times out after a few seconds.

Switch options

Since it is vital that the system be adaptable for those with different disabilities and preferences there are numerous input options. These may be set up using the assembler file SWITCH. An alternative assembler file SWSETUP provides a more "user friendly" method of selecting the options. The options are:

* The number of switches may be 1, 2 or Joystick (4). Obviously switches may include suck/puff switches etc.
* The arm may be commanded to move either by holding the switch down, or alternatively initiated by pushing the switch and stopped by pushing the switch again. This latter is better for a suck/puff switch where it is not possible to maintain a suck or puff for a sustained period.
* The scan is either down from top to bottom and then repeat from the top again or in a circular fashion from top to bottom and then up from bottom to top etc. There are then further switch options depending on the number of switches.

1 switch: Scanning will be always at a pre-set rate. For a simple menu, selection may be either by pressing the switch to initiate the scan and releasing to select or by the cursor scanning automatically with a switch press to select. For selection from the direct movement menu a further option is to press to scan and release to select vertically, but horizontally use the automatic scan, press to select. When a direction has been selected the arrow symbol changes colour to

signify selection. The switch must be pressed again to initiate the movement, or if not pressed within a few seconds it times out and returns to the vertical scan.

2 Switch: One switch is used to scan through the list, either releasing the switch each time or alternatively with an automatic repeat if the switch is kept pressed. The other switch is then used to select the option. For selection from the direct movement menu the method is to use the first switch to scan down, the second to scan across and the first again to initiate movement.

Joystick: The joystick used is a four switch digital joystick. Scanning up or down uses the North/South axis of the joystick. Selection uses either the East or West direction. For the direct movement menu the East or West directions are used to initiate the movement in the direction of the right or left arrow respectively.

* The system may make a "beep" or a "click" sound as the cursor scans or as a selection is made.
* Variable timing parameters may be specified for scanning repeat delay and period. The timings may be different for scanning in the vertical and horizontal direction. Also an anti tremor delay may be specified for those users who suffer from physical or intention tremor.
* When the cursor is scanning automatically (particularly with the "beep" turned on) the constant movement or noise may be irritating. Therefore after a specified number of scans of the

menu the cursor will stop, till the switch is pressed to reactivate the scan

The scanning of the cursor and response to switch presses is controlled by interrupt driven events every 1/50th of a second. When the switch code is assembled only the appropriate event routines for the options specified are assembled. Other switch options, for example beep on/off or scanning direction are controlled by the use of flag bytes.

ROBOT CONTROL CALLS

Op-Code Hex	Dec	Name	Description	Location
00	0	initialise	Initialise system	DIRECT
01	1	robotreset	Reset robot position	DIRECT
02	2	robothome	Send robot to park position	DIRECT
03	3	robotsoft	Send robot to home position	DIRECT
04	4	directmove	Move arm under direct control	DIRECT
05	5	motorread	Read motor joint positions	DIRECT
06	6	posread	Read current xyz position	DIRECT
07	7	currentrst	Reset current limit	DIRECT
08	8	counterrst	Reset counter	DIRECT
09	9	brake	Motor brake on/off	DIRECT
0A	10	speedmode	Change speed mode	DIRECT
0B	11	setsofthome	Set/read home position	DIRECT
0C	12	ecuset	Set/read environmental control	DIRECT
0D	13	ecutext	Read/write appliance name	DIRECT
0E	14	powerset	Set/read power control	DIRECT
0F	15	directspd	Set/read speed for direct mode	DIRECT
10	16	runprog	Run program in memory	REPLAY
11	17	runlines	Run program lines	REPLAY
12	18	contprog	Continue prog (after interrupt)	REPLAY
13	19	movepos	Move to position	REPLAY
14	20	-	spare	REPLAY
15	21	-	spare	REPLAY
16	22	uservalues	Set/read speeds	REPLAY
17	23	-	spare	REPLAY
20	32	mergelines	Merge lines	EDIT
21	33	deleteline	Delete line	EDIT
22	34	readline	Read line	EDIT
23	35	writeline	Write line	EDIT
24	36	insertline	Insert line	EDIT
25	37	absrel	Swap absolute/relative moves	EDIT
30	48	clearcreate	Clear create routine area	ROUTLS
31	49	clearstart	Clear start routine area	ROUTLS
32	50	transferprog	Transfer routine	ROUTLS
33	51	loadprog	Load routine	ROUTLS
34	52	saveprog	Save routine	ROUTLS
35	53	readdirname	Read directory name	ROUTLS
36	54	readprogname	Read routine name	ROUTLS
37	55	writedirname	Write directory name	ROUTLS
38	56	writeprogname	Write routine name	ROUTLS
39	57	deleteprog	Delete routine	ROUTLS
FF			Exit Machine Code	CMAIN

Table 12.1

Op-codes used in routines

```
01    MOVETO       Move to absolute position
                   b0: code 01
                   b1-10: position in xy format
                   b11: speed

02    MOTOR        Move motor (relative)
                   b0: code 02
                   b1: motor number
                   b2,3: displacement
                   b4: speed

03    MOVE         Move relative
                   b0: code 03
                   b1-10: displacement
                   b11: speed

04    PAUSE        Pause routine
                   b0: code 04
                   b1,2: pause time (centiseconds)

05    ADJUST       Return control to user to adjust position
                   b0: code 05

06    PARK         Move to parked position
                   b0: code 06

07    HOME         Move to home position
                   b0: code 07

08    WAIT         Wait till user switch pressed
                   b0: code 08

09    CONTROL      Turn on/off controlled mains appliance
                   b0: code 09
                   b1: device number
                   b2: 1=on, 0=off

10    LOOP         Repeat loop in routine
                   b0: code 10
                   b1: 0=start of loop
                       1-&7F=loop "n" times
                       &80=loop again
                       &81=loop again if requested by user

11    GRIP         Actuate gripper
                   b0: code 11
                   b1: gripper state code
                   b2: position

12    SETSOFT      Set home position
                   b0: code 12
                   b1-10: position in xy format
                   b11,12: gripper state/position
```

Table 12.2

MEMORY USAGE - EUROBEEB SYSTEM

name	type	start	finish	used	total	note
loc0%	local	E00		07	20	cmain
loc1%	variables	E20		13	20	direct
loc2%		E40		16	20	replay
loc3%		E60		0A	10	edit
loc4%		E70		26	30	routls
loc5%		EA0		02	10	home
loc6%		EB0		00	10	gripper
loc7%		EC0		31	80	motor
loc8%		F40		14	20	calcxy
loc9%		F60		39	60	utilM
loc10%		FC0	FFF	16	40	utilA
var0%	shared	1000		07	40	global
var1%	variables	1040		0D	20	utility
var2%		1060		41	60	motors
var3%		10C0		25	40	move
var4%		1100		24	40	calcxy
progcreate	data	1200			600	routine
progstart	data	1800			600	routine
block%	RS423	1E00			80	interface
userc%	const	1E80			80	data
ctrlmen%	data	1F00		70	80	ecu
progcat	data	2000		2A0	2A0	catalogue
progstore		22A0	3FF0			routines
cmain%	program	4000		35A	400	M.ROBOT
direct%		4400		468	600	
replay%		4A00		527	600	
edit%		5000		4CA	600	
routls%		5600		498	600	
home%		5C00		2A3	300	
gripper%		5F00		1AE	300	
motor%		6200		736	800	
calcxy%		6A00		59D	600	
utilM%		7000		528	600	
utilA%		7600	7C00	5A2	600	
xytable%	const	7C00			100	look up
sysc%	const	7D00			300	data
mmap%	motor etc	FE40				i/o

Table 12.3

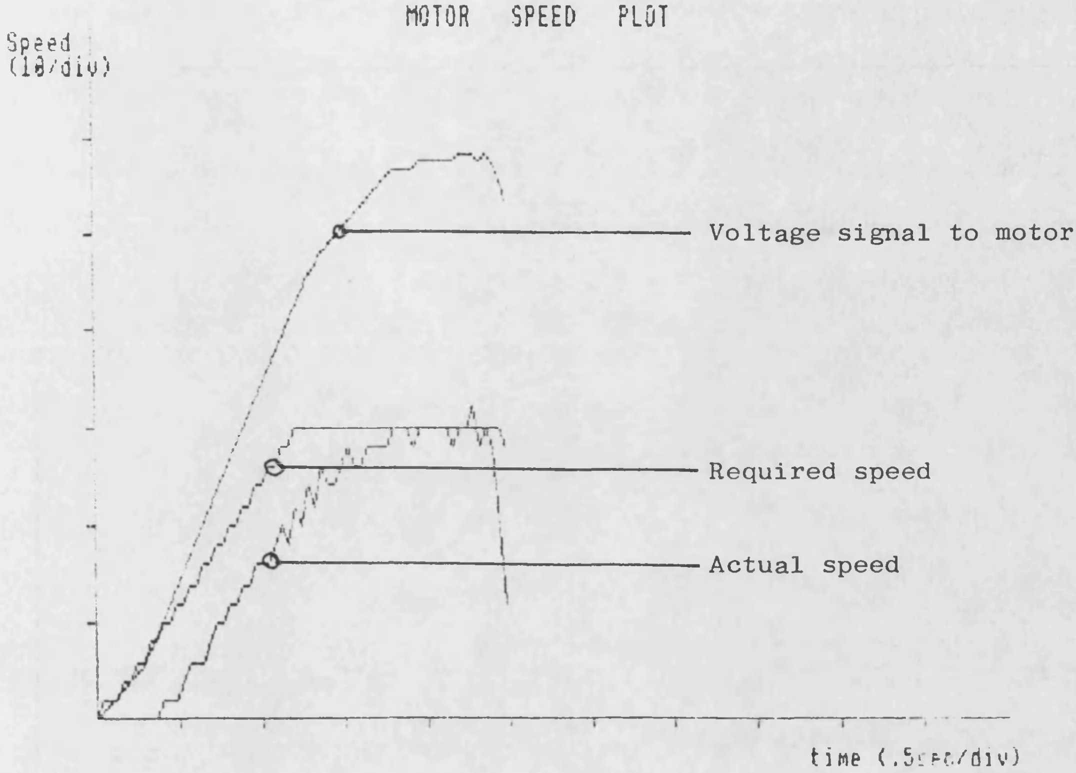
MEMORY USAGE - INTERFACE

name	type	start	finish	used	total	note
loc0%	variable	7B00		00	10	MAIN
loc1%		7B10		04	10	MENUS
loc2%		7B20		06	20	EDIT
loc3%		7B40		09	20	SCREENS
loc4%		7B60		0A	10	SWITCH
loc5%		7B70		01	10	ERROR
loc6%		7B80		17	20	UTILITY
var0%	variable	7BA0		07	10	utility
var1%		7BB0		25	30	screen
block%	RS423	7800			20	
scdat%	variable	7820			C0	screen
vecdat%	variable	78E0			20	vectors
edscdat%	variable	7900			200	edit scr
header%		8000		0AD	100	
main%	program	8100		418	500	
main%	(short)	8100		361		
menus%		8600		8B7	900	
edit%		8F00		814	900	
screens%		9800		5A7	700	
switch%		9F00		(3F2)	500	
error%		A400		3A2	500	
utility%		A900		515	700	
helptxt		B000				help text

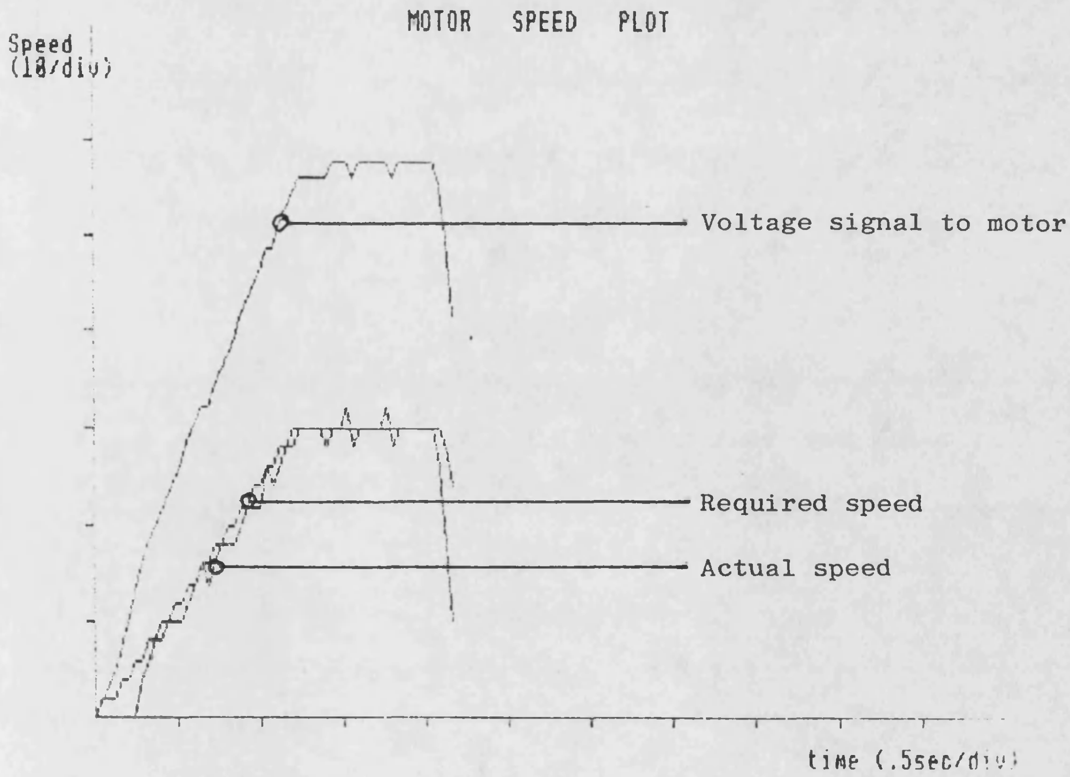
Table 12.4

BBC USER COMPUTER		EUROBEEB CONTROL COMPUTER
Clear buffers		Clear buffers
Write 01 = Ready	>	? 01
		If N: Restart loop
? 00	<	If Y: Write 00 = Ready
If N: Restart loop		
If Y: Write opcode	>	Read opcode
Write size of data	>	Read size of data
Write data	>	Read data
		? data OK
		If N: Write OF = Error Restart loop
? 02	<	If Y: Write 02 = OK
If N: Write OF = Error Restart loop		
WAIT		OPERATION
? 03	<	Write 03 = End of routine
If N: Continue WAIT		
If Y: Read size of data	<	Write size of data
Read data	<	Write data
? data OK		
If N: Write OF = Error Restart loop		
If Y: Write data = OK	>	? 02
		If N: Write OF = Error Restart loop
Start of loop		If Y: Start of loop

Data communication between BBC and EuroBEEB Fig. 12.1

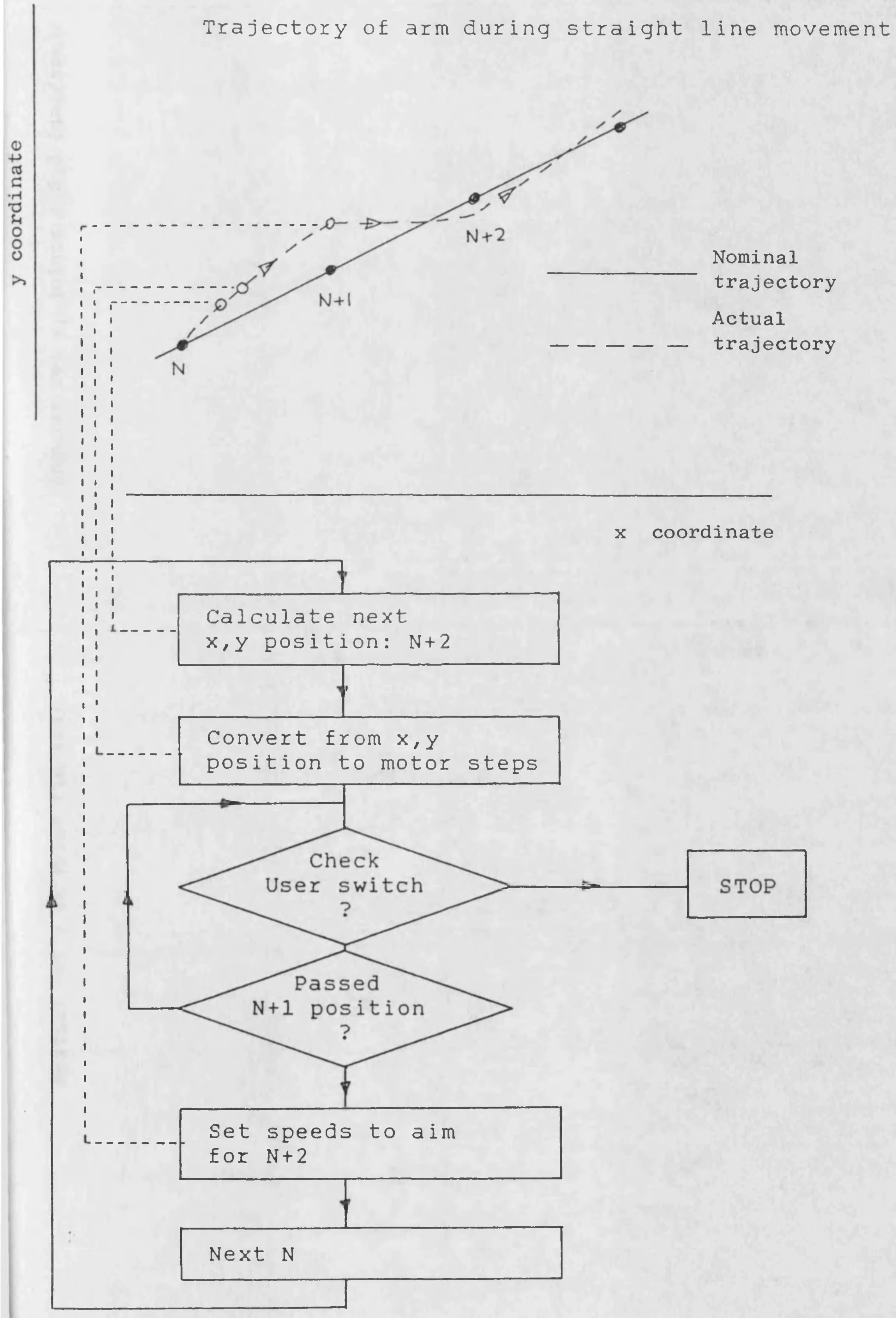


Before tuning



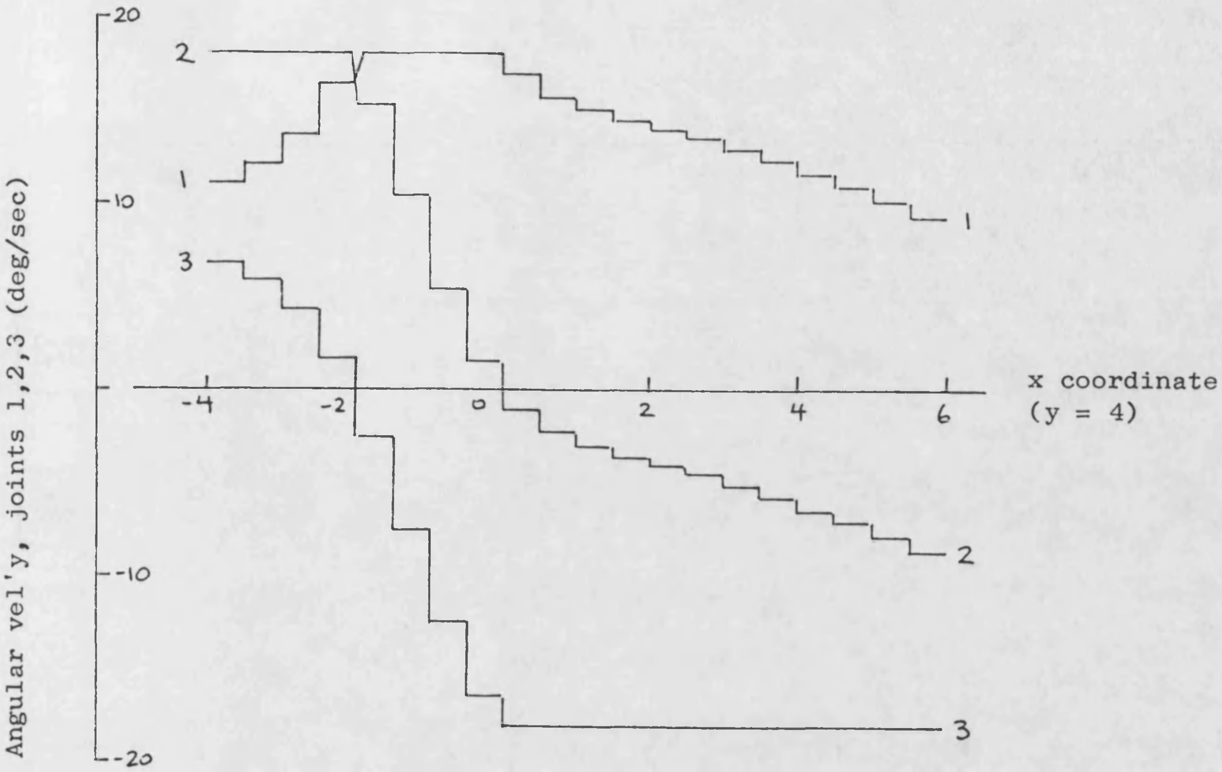
After tuning

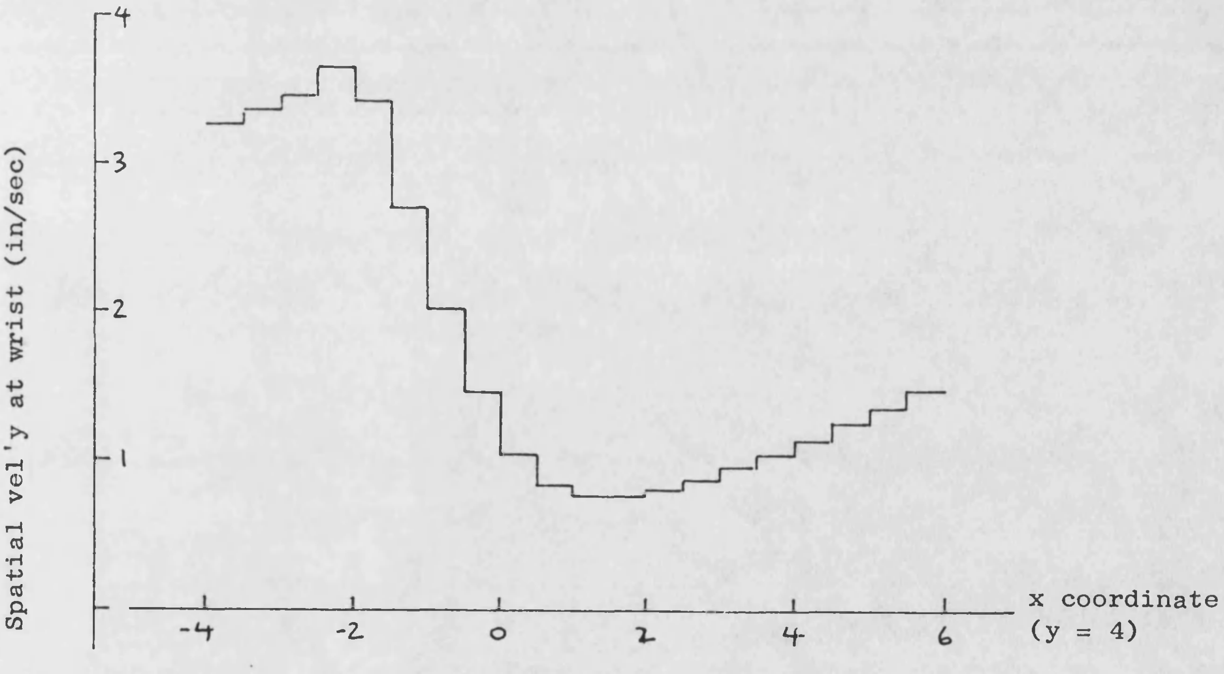
Motor speed plots Fig. 12.2



Straight line algorithm

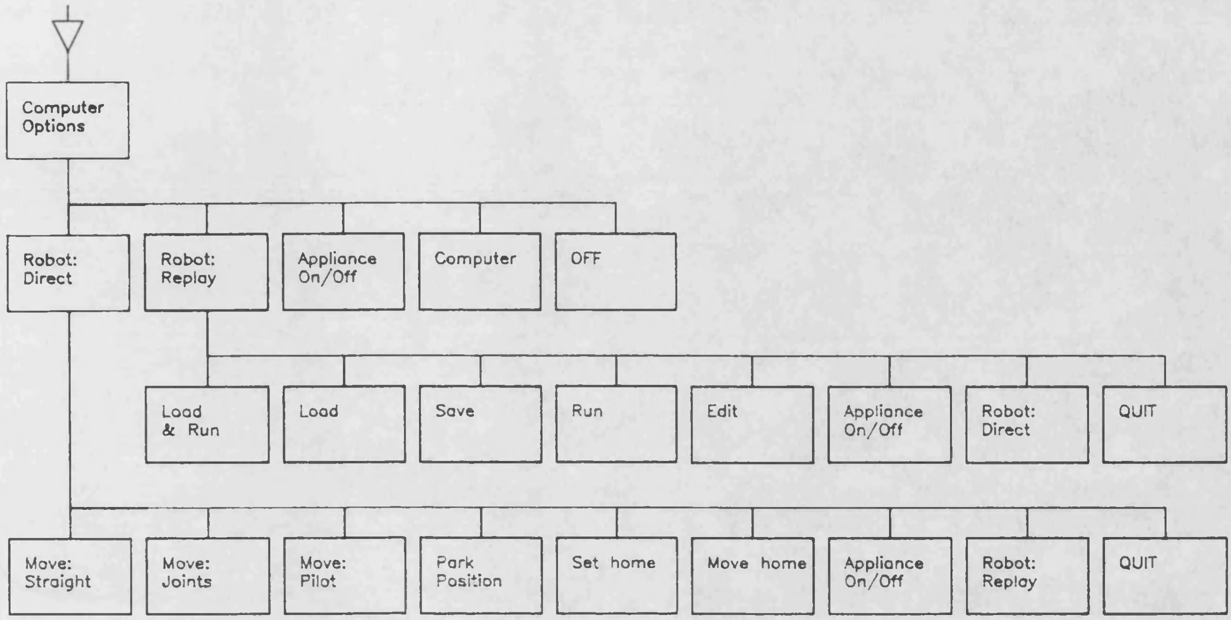
Fig. 12.3



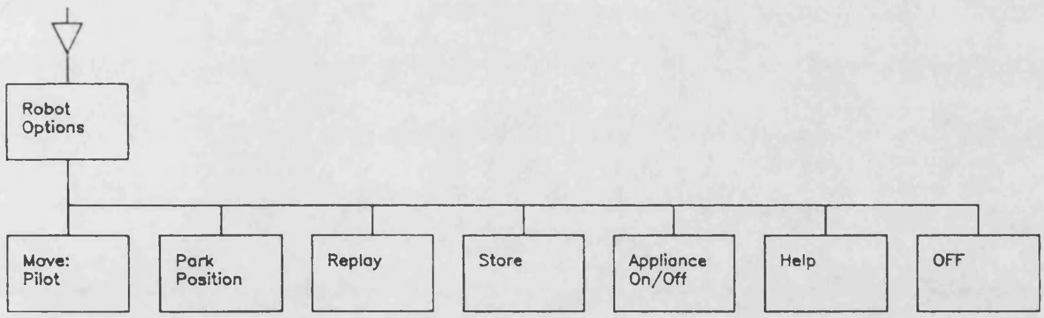


Typical angular and spatial velocities of wrist during straight line motion.

Fig. 12.4

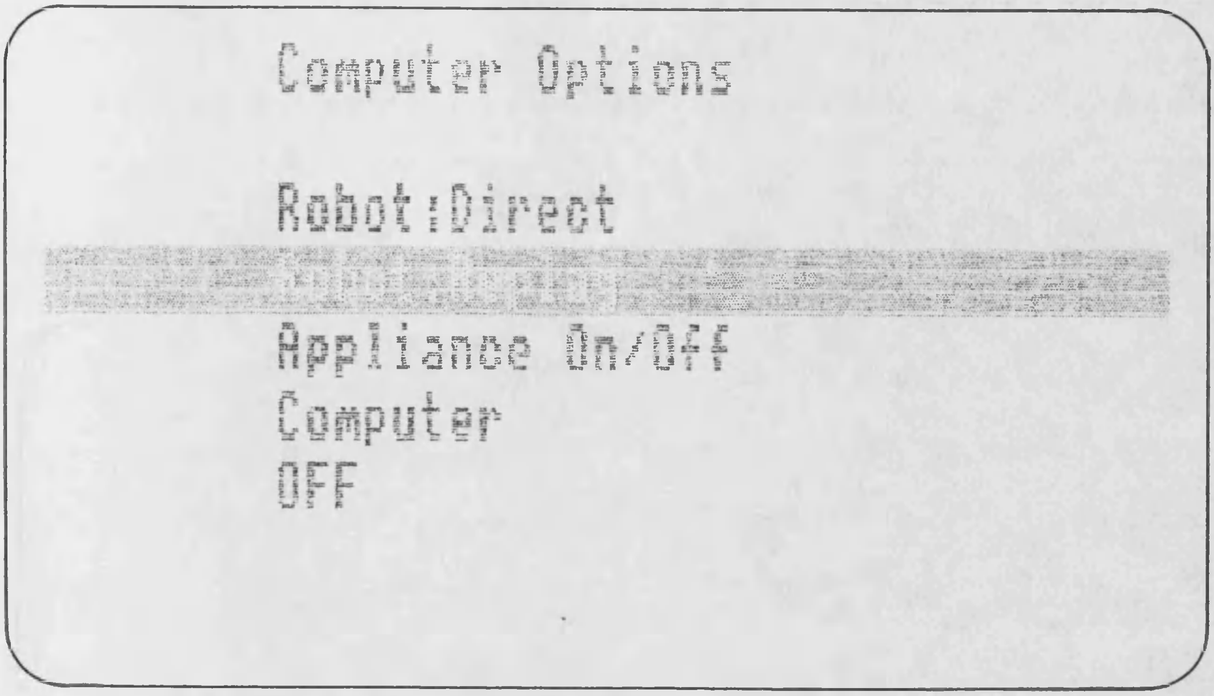


a) Long Menu Tree Structure for Robot User Interface.

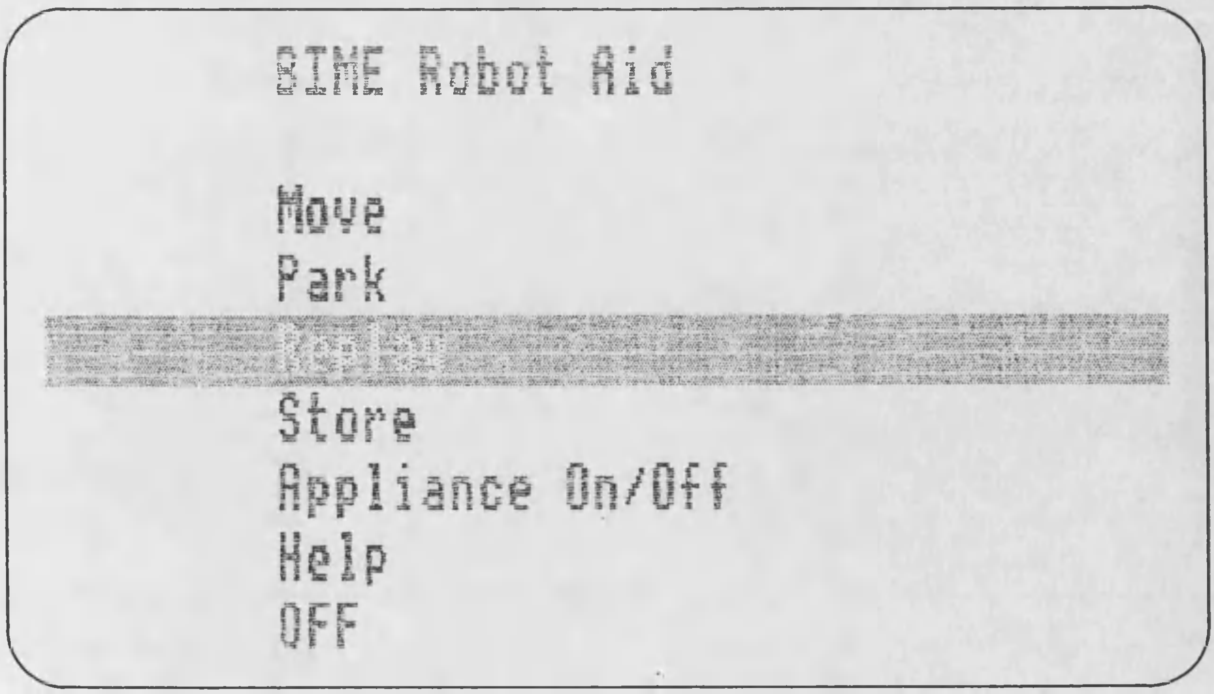


b) Short Menu Tree Structure for Robot User Interface.

Menu tree structures for robot user interface Fig. 12.5

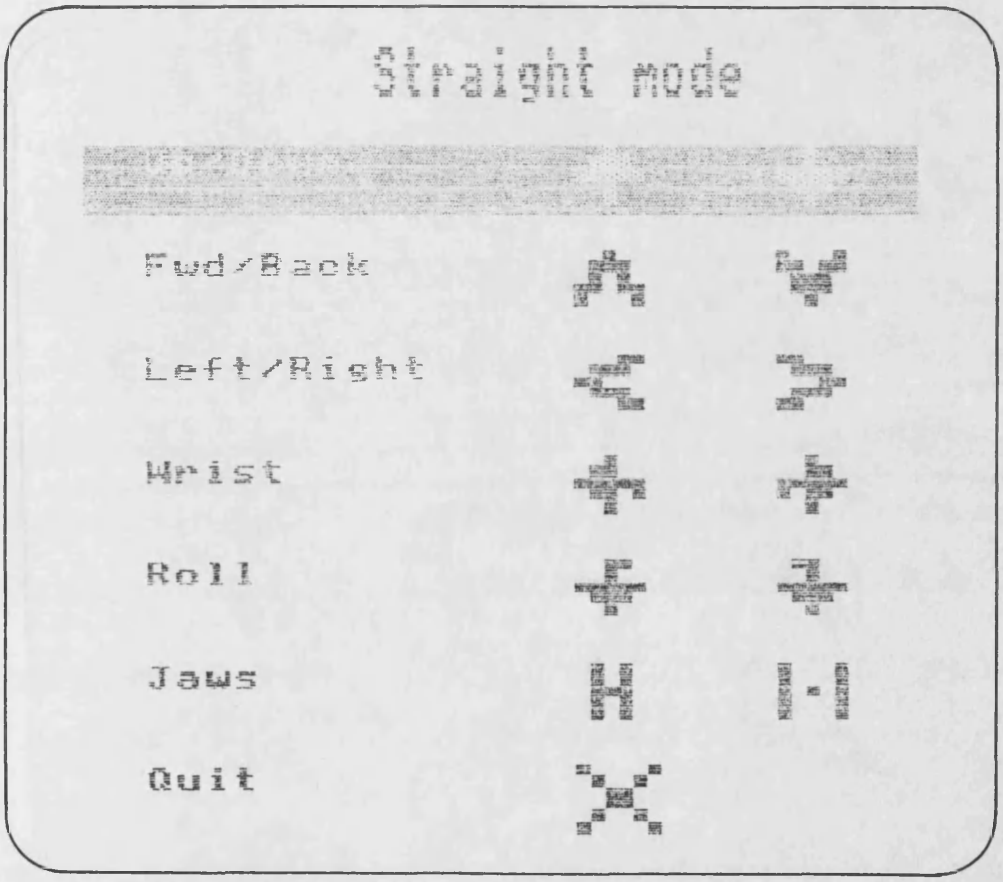


a) Initial menu screen (long form)



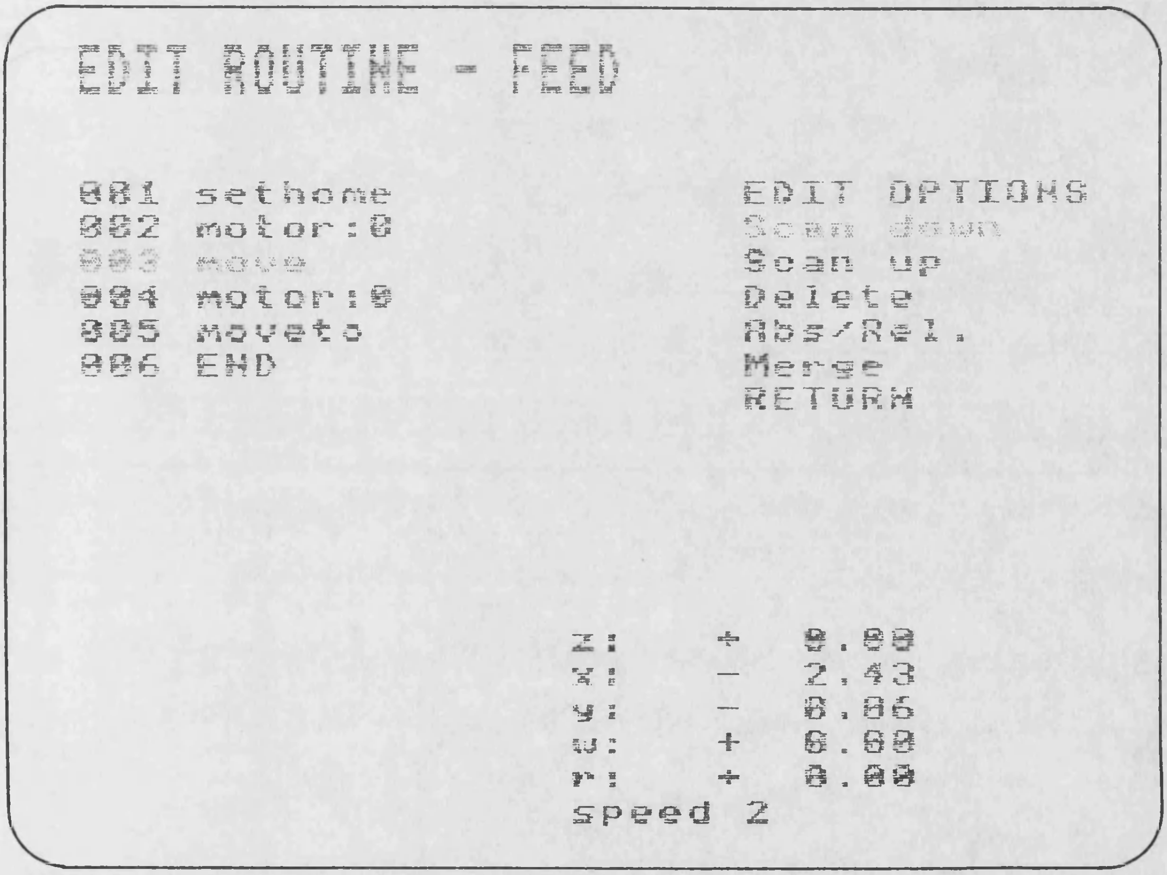
b) Initial menu screen (short form)

Fig. 12.6



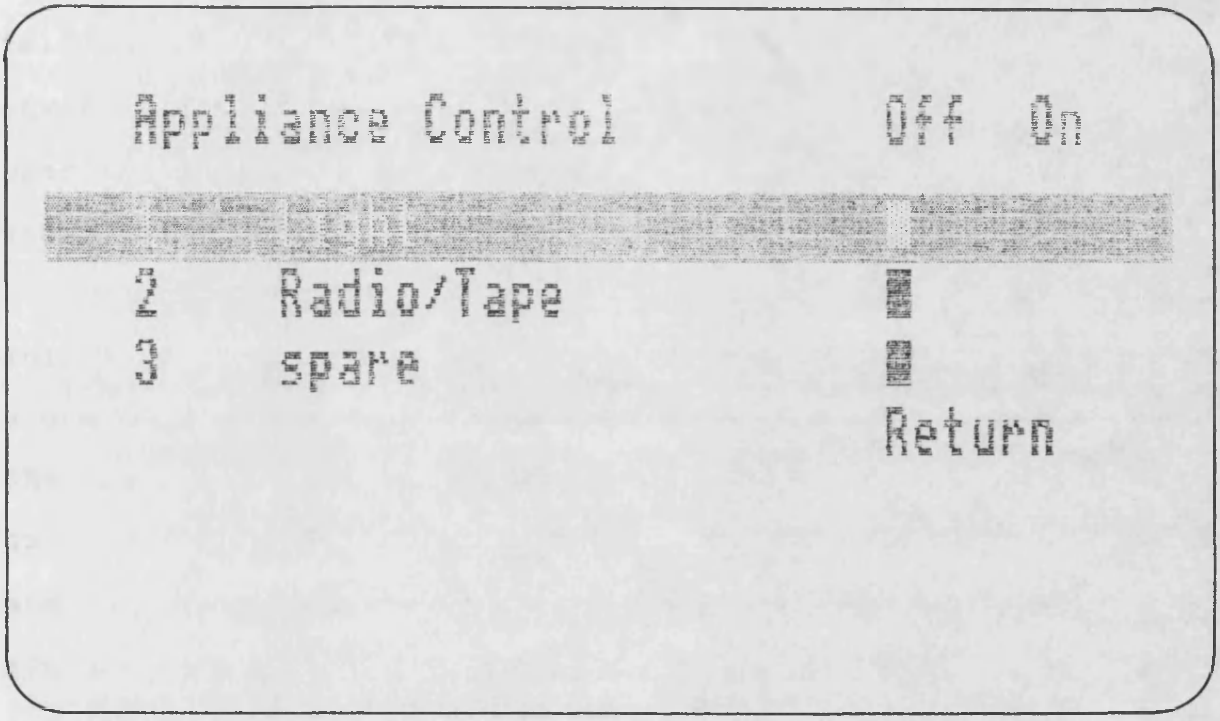
Menu screen for direct movement control mode

Fig. 12.7



Screen display for editting of routine

Fig. 12.8



Screen display for environmental control facility.

Fig. 12.9

Chapter 13. WOLFSON WORKSTATION ROBOT - USER TRIALS.

INTRODUCTION TO TRIALS.

With the previous system the trials were carried out primarily at the Duke of Cornwall, Spinal Injuries Unit at Odstock Hopsital, Salisbury. These trials were valuable but it was felt that trials with a robot system in people's home or work environments would give a better view of the ultimate usefulness of such a system. The tests at Odstock were however useful in evaluating the performance of the system.

Initial trials of the Wolfson system involved a day's visit to a user's home to get feedback to assist in the refinementof the system for later more extensive trials. Trials at Odstock hospital were deliberately limited to a much shorter period and involved 4 patients. Interviews were also held with the OT staff at the unit. Subsequent trials were held with three individuals visiting the institute to use the system and longer term trials in two domestic situations.

INITIAL TRIALS

The system was transported to the home of a gentleman with multiple sclerosis on 16th Oct 1991. This person had been involved in the feasibility study and has maintained an interest in the robot project and the work of the Institute. His comments are valued. The system was essentially working satisfactorily under direct control, though the replay of routines was not implemented at that stage.

The manipulation of cassettes was demonstrated, and the subject was able to control the manipulator to do this himself. The arm was also demonstrated inserting a disc and operating the controls on a microwave. It was found that some of the microwave controls were too stiff for the arm operating in a horizontal plane.

The subject found the appearance of the robot pleasing particularly in comparison to the Atlas robot. The size of the desk was not a problem. When the maximum extension of the arm was demonstrated, near the subject's head, he stated that he did not find it at all intimidating. He found visibility easy, apart from the problem of parallax.

He made some valuable comments on the interface system, particularly in comparison with the Possum system which he was used to for environmental control and computer access. Many of his recommendations were implemented. He used a double switch input, but would have preferred a single switch input (not implemented at that stage).

He filled in a copy of the questionnaire, as had been used at Odstock for the Atlas workstation system. He was satisfied with all aspects of the system, though thought that the interface could be improved. He considered a cost of £10000 would be acceptable for the system. His answers to the questions are incorporated in Tables 13.1 to 13.6 (subject "G") and are discussed later.

TESTS AT ODSTOCK HOSPITAL

The system was transported to Salisbury on 20 March 1991, and returned on 11 April 1991. Besides transport a further 7 visits were made to Salisbury. On these vists 6 sessions were spent with 4 patients, and 3 questionnaires were completed. The questionaires were based upon, but modified slightly from, those administered earlier.

Performance of system at Odstock.

The hardware performed satisfactorily. It had been feared that the system might crash (due to spikes to the electronics from the vertical actuator), but though this did happen a few times it did not prejudice the trials. However, for trials in users' homes this must be sorted out. At one point the system went down due to a loose connector.

The performance of the straight line movement was adequate, and none of the users complained about the wobbliness of the motion. However the replay was not accurate enough. In part this was due to the zero position being set slightly differently after each reset. This has subsequently been modified, though the accuracy is still not adequate.

Users reactions

Three patients used the system, of whom two filled in the questionnaire (the third was confined to bed when we came to the interview stage, and so it was not possible to get his response). A fourth patient had the system demonstrated but did not use it himself.

Subject H. Female .. Aged 41 .. Married

This subject had one session using the system, and a second discussing it and filling in the questionnaire. She controlled the system using a suck/puff switch in single switch mode. She found the control of the system relatively easy, although she did not find the order of the horizontal scan on the move menu logical. She also commented that she found the visibility poor due to the bulk of the gripper obstructing her view of the end of the jaws.

She was generally enthusiastic about all aspects of the system, and felt that it would be useful in her situation as a secretary. She was an enthusiastic user of the Apple Macintosh

Headstart system and said that if the robot was integrated with the Headstart system it would be "beautiful". (Headstart is a mouse emulating input device and windows environment software for the Macintosh. Head position is monitored by ultrasonic transducers mounted on a headset with the ultrasonic source on top of the monitor, thus emulating mouse movement. This system is used for computer control, though there is also an environmental control facility.)

She very realistically estimated the cost of the system as being about £4000 to £6000, and regreted that she could never afford such an amount.

Subject I. Male .. Aged 22 .. Single

This subject had two sessions with the system and was quickly very competent. After only one session he was able to demonstrate the system to watching OTs, unhindered by the presence of an audience. He used a suck/puff switch in single switch mode. He used a chin joystick on his electric wheelchair and would have preferred this form of input to the robot system.

This subject also was very enthusiastic about the system. As a student he is familiar with computers, and possibly considers a career in journalism or publishing. Thus access to a Desk Top Publishing system would be valuable for him.

Subject (AH) Male (Did not fill in questionnaire)

This subject used a hand joystick to control the robot which he found adequately easy. He described himself as "not a computer user". He didn't consider the system appropriate for himself, being able to lift a cup by himself and to control an electric wheelchair.

Subject J. Male .. Aged 27 .. Married

This subject did not use the system but was happy to have it demonstrated and to respond to the questionnaire (as much as was applicable). If he had used it he would have controlled it using a single hand switch. He was only interested in a system which would reliably carry out tasks with no user intervention. He envisaged a system with a row of buttons, each initiating a task such as loading a CD or a tape.

INTERVIEWS WITH OTs

Interviews were held with five of the OT's at the Spinal Unit. Of these, two had not used the robot, and one had not seen the previous Atlas workstation. The interview was divided into five sections.

Appearance.

Initial comment on the appearance was in relation to the earlier Atlas system which was thought to have been excessively large. The Wolfson system was considered to be a large improvement, though it still might be too large for many people's domestic accomodation, particularly with the other extra equipment which disabled people need to accomodate in their homes. However it was good that it did not need any structural work to the room/house to install. The therapist who hadn't seen the earlier system had expected a much smaller device.

The reaction to the oak finished desk was not enthusiastic. It was considered to look old fashioned, rather than "hi tech". Part of this reaction may have been due to the large task cabinet at the rear.

The movement of the arm was considered too slow for the replay of routines, which should also be more effective and reliable. It was commented that a more "fluid" motion had been expected, similar to the the movement of a human arm. Noise was unobtrusive.

Tasks/usefulness

They considered that the main application would be in a vocational application (this is very much the emphasis of the department's work). Also the use of the robot for games and the operation of home entertainment equipment was appropriate.

There was a negative reaction to the use of the robot for feeding or personal hygiene. This was mainly because feeding is considered a social activity and use of the robot would remove human contact. There would also be problems with the use of a suck/puff switch for controlling a feeding application. It was however considered that it might be possible (though difficult) to use the robot for food preparation. A drinks machine might also be incorporated on a vocational workstation for when the user became thirsty.

Obviously the robot could be used for simple picking up and movement of various objects, but then the user would have to be able to do something useful with whatever object had been moved. Many of the tasks which the robot might do could also be done by an environmental control unit.

Control methods

Most of the patients who go through the department become familiar with a scanning control method. By comparison with some other scanning type interfaces, this was considered to be a good implementation. However scanning systems are by their nature slow. Some of the symbols used for the direct menu screen were found to be confusing (particularly the jaws open/close which was subsequently modified). It was stated that the use of different switches was a very individual choice, dependent on physical ability and personal preference.

Much comparison was made with the Headstart system which operates on the Apple Macintosh computer. The OTs rate the Headstart system highly and would have liked a similar interface for the robot.

Emphasis on robot control should be on the use of routines rather than direct control for ease of use. Some patients however like the challenge of direct control while others are put off by it. One of the OTs though that it was motivating for a user to be able to program a routine himself and then be able to replay it. Replay of routines must be reliable.

Comment was made on teaching people to use the system. This should start with very simple instructions and limited options, only progressing to the more advanced facilities when the basic control was well understood.

Cost

The cost was quoted as being of the order of £6000. Some of the OTs felt that the system did not look like £6000 worth of equipment. This was in part due to their feeling that it did not look hi-tech enough. In this country there are not many compensation cases and therefore most people would not be able to afford it. However if the Department of Health could be persuaded to provide the equipment this would not be a problem. The price was felt to compare favourably with that of the Possum environmental control system.

Robot applications: Workstation / Mobile robot / Wheelchair mounted

A workstation based system was thought to be most appropriate for an employable person.

The use of a wheelchair mounted robot opens up many possibilities because of its mobility, though there are associated problems. The arm would need to be fixed to different wheelchairs (and the Department of Health's resistance to any modifications to their wheelchairs was noted). It was important that a person's chair shouldn't be weighed down by lots of gadgets, rather the person using the chair should always be the focus of attention. The size of the arm might be a problem, and this was particularly commented on in the context of transfering the disabled person onto and off of the chair. Since replay of routines is no longer a viable option, control by direct methods would be more of a burden. Opening of doors is a major problem for wheelchair bound people which a wheelchair mounted manipulator might be able to assist with.

The idea of a mobile robot did not receive much comment either for or against.

Conclusions

The general feeling was that, in line with the priorities of the department, the robot system would be most applicable in a vocational environment. In particular there was a strong feeling against its use for feeding. The OT's were not convinced about the reliability of operation of the system, though they were open to the general potential of a robotic system.

TESTS AT BIME

Three people, living in the Bath area, were invited to visit the Institute to test the robot system. Of these two had motor neurone disease and the third multiple sclerosis. While being enthusiastic about the potential of the system none felt that it would be of use to them in their own situations. None of the three were asked to fill in the questionnaire.

Subject (Be) Male .. Aged 47 .. Married .. Motor Neurone Disease

This volunteer, previously an electrician, had had MND for more than 5 years. He was just about to have a Possum system installed, but was in general resistant to using gadgets if he could do anything himself.

He felt that the lack of mobility and reach was a major shortcoming of the system as he would need to pre-plan his day around the robot. It would be difficult to find space in his house to fit the system. He found the desk too high for someone sitting in a chair (it was designed around someone in a wheelchair). He used a joystick to control the robot with no problems.

Amongst the tasks discussed were feeding and making a drink, gardening, and manipulating books. He was not sure about using the robot for shaving or cleaning teeth. He felt that it would not be of use for using a TV or video since he would use a remote control unit. For drinking he would use a straw with the cup simply placed on a table top.

Subject (Br) Male .. Aged ?60 .. Married .. Motor Neurone Disease

This subject used the robot with a single foot switch. Initially this was a standard hand switch (as used regularly with the robot) but it was felt to have insufficient feedback in a situation where it cannot be seen. For a second visit a connector lead was constructed so that the subject's footswitch, normally used for his ECU could be used. This was better. However, due to the height of the chair being different and having the switch on a hard floor rather than carpetted, it was not as easy to use as in his home.

Apart from problems with the switch some useful comments were made concerning the control of the arm. He felt that the arrow symbols should be clearer so that he didn't need to concentrate on what the symbols meant. Another problem was what to do when a false selection was made in the move menu. The software was subsequently modified so that if a false selection is made, but movement not initiated within a few seconds, the system will time out and return to the vertical scan.

Though willing to make positive criticisms about the control of the robot this subject was not so forthcoming with comments about the usefulness of the system. It would however seem to not be much use in his situation, and he was not interested in having it for a period at his home.

Subject (El) Male .. Aged ?40 .. Single .. Multiple Sclerosis

This subject controlled the robot using a joystick input, which he found relatively easy to use. In common with other sufferers of MS his eyesight has deteriorated which he finds especially a problem when tired. He did not find the colours used on the screen easy to read, and would have found a dark colour on a light background easier. He also would not want a smaller screen, though if mounted closer to his eyes this might be satisfactory.

At present he has sufficient ability to not benefit from a robot system, but would be interested in using such a system in the future if his condition deteriorates. He was very interested and enthusiastic about the concept of a wheelchair mounted robot, and by comparison found the workstation concept inappropriate. The main application he was interested in was for feeding or drinking.

HOME TESTS

Since the tests of the Atlas system at Odstock Hospital it has been felt that the most valuable feedback would come from long term trials in people's own homes or workplaces. In order to find volunteers for these tests we first contacted those who had use the Atlas system while at Odstock and were now at home. Of these two were not considered appropriate to contact, another has since died, another had made a good recovery and would not benefit from the robot. One person was willing to help but it was judged that she lived too far away. Therefore of the original six, only one was appropriate to help at this stage (previously subject C).

For these trials it was decided to change our approach regarding the way the workstation was presented. Previously the task cabinet had a number of tasks incorporated with a computer prominently on the desk top. It was felt that presenting these set tasks might prejudice people's reaction to the system, particularly those who were not computer users. Therefore the task cabinet was replaced by smaller individually placeable units for the tape player and for books. The computer itself was mounted in the electronics cabinet, with only the monitor on the desk top. Also the shorter form of the interface menu was introduced (whereas up to this stage the full menu had always been used). At the request of the user the height of the desk top was increased so that he could wheel his electric wheelchair underneath.

Subject K   Male .. Aged 41 .. Married .. Spinal Injury

The robot was placed in the home of this person for about 3 weeks. During that period we made 5 visits. He used the system on his own at other times, and was keen to show it to visitors. For the last week he was not able to use the system very much, due to back problems caused by an inappropriate wheelchair. The system proved satisfactory in use without our presence. The only technical problem was a fault with the interface software, caused by a computer fault on the sideways RAM board. This was easily corrected.

He used a single switch input to the system. He found the standard hand switch difficult to use due to the low tactile feedback, and found that he had to be constantly looking at the switch to check that he was pushing it satisfactorily. Subsequently we made up a connector lead so that he could use his environmental control switch which he was familiar with, and which had a more positive audible and tactile feedback. Having sorted out the input device he found the system easy to use.

He enjoyed using the system and experimented with feeding, drinking, using the tape player and manipulating chess pieces and books. Feeding was initially performed using a bent tablespoon, using the roll action to dip the spoon into a bowl of breakfast cereal. Following discussion, a new spoon was made up in a shovel shape which was easier to use. He thought that feeding would be useful if a carer was not present, but found it tedious to carry out using direct control. It was not possible to develop ideas further, due to the back pain problems mentioned above. In spite of our efforts not to present the system as being computer oriented he thought that computer use would be a major area of its application.

Subject L Male .. Aged 41 .. Married .. Motor neurone disease

This user was very enthusiastic about all aspects of the robot system. He was keen to investigate and experiment with all possible applications of the robot. He identified tasks which the robot might be able to carry out rather than waiting for us to suggest applications. He spent a considerable period perfecting page turning. Thin sheets of clear plastic (OHP transparencies) were inserted between the pages of a book, with a tab cut into the edge. The robot was therefore able to turn the pages by lifting the tabs. He was grateful to have the robot bring his beaker of coffee to him, rather than calling to his wife. He has also used the robot for inserting cassette tapes and computer discs. The tests are continuing and he intends to investigate the use of the robot for feeding, washing and cleaning teeth.

He was introduced to the control of the robot using a hand operated switch. However he experimented with different switch positions and found it easiest to operate the switch with his feet, having removed his shoe and sock. He was able to accurately control the robot under direct control and also to set up his own replay routines.

The workstation was set up in a small upstairs bedroom. This presented two problems. Firstly the workstation only just fitted in the room. Secondly it proved very diffcult to move the robot upstairs. Though the workstation could be dismantled, the cabinet housing the robot was very heavy to lift and could only just be manoeuvered past the stair lift. It was felt that the system would be much more useful if it was smaller, could be installed downstairs and made more easily transportable.

The only fault with the robot system was due to corruption of the motor speed data in the EuroBEEB battery backed memory, causing the motors to move erratically. This might be due to a false signal on the parallel bus or a fault condition at power on.

RESULTS FROM QUESTIONNAIRE

The subjects who used the system are arranged in chronological order of use. For some of the questions one or other of the subjects did not respond for various reasons. This is particularly true for subject J who did not actually use the system. Table 13.1 lists the users and summarises their situations. Subject G was tested at his home on a single visit, subjects H,I and J during the period at Odstock hospital and subject K for a period of three weeks in his own home. Subject L is still using the system, having had it for a period of two months.

Patient identifier	Age	Sex	Marital status	Lesion level	Test location
G	55	M	Widower	(MS)	Home
H	41	F	M	C4	Odstock
I	22	M	S	C4	Odstock
J	27	M	M	C3/4	Odstock
K	41	M	M	C3/4	Home
L	41	M	M	(MND)	Home

	Previous employment.	Computer experience.
G	Accountant (still working)	Yes
H	Secretary	Secretarial, home computer
I	Student	Yes
J	Farm worker	No
K	Engineering inspector	No
L	Royal Marines - Instructor	Wordprocessing, home computer

Table 13.1. Wolfson Workstation, 1991. Details of users.

Overall rating (Table 13.2)

Many aspects of the new system got very good ratings in comparison with those areas of the Atlas system which had been rated poorly. Lack of noise is a very good feature of the system. Reaction to the speed varied, though the difference is due to those who were more concerned with the speed in direct mode which was rated well, compared with those who were more concerned with the speed of replay which was considered too slow. The questions relating to the appearance and layout of the system were rated well. Visibility was only rated satisfactory due to the bulk of the gripper. The appearance of the arm itself was moderately successful, one person saying that it should be slimmer, and two others requesting a more rounded appearance. Another said that he liked the metal appearance. Potential usefulness was rated good by those who would have used it in a computer based vocational environment.

	Good	Satisfactory	Poor
Noise	GHIJKL		
Speed	GHL	I	JK
Layout of workstation	GHIJKL		
Visibility	GI	HJKL	
Appearance of workstation	GHJ	IKL	
Appearance of arm	GK	HIL	J
Ease of use	L	GHI	
Potential usefulness	HIL	K	J

Table 13.2. Wolfson Workstation, 1991. Overall rating.

Input device (Table 13.3)

Ease of use (previous Table) was only rated satisfactory, due to limitations of a single switch scanning system, particularly in comparison to systems such as Headstart or a chin joystick input. On the basis of feedback from earlier tests we concentrated on the use of a single switch input rather than a two switch input. This would appear to have been a successful change.

Subject L found it most convenient to operate the single switch using his foot and this would seem to be common experience for motor neurone disease sufferers. It may be noted from the table that the majority of users, even high lesions, were familiar with an analogue input of some kind and this may therefore be a more appropriate means of controlling the robot.

	Used in tests	Familiar with (+)	Preferred
Suck/puff (*)	HI	GL	
2 switch	G		
1 switch	KL	G	GKL
Chin joystick		HI	I
Headstart		HI	H
Mouthstick		I	
Handstick		K	
Headstick		L	
Joystick		GKL	

Table 13.3. Wolfson Workstation 1991. Input devices.
(+ Familiar with and able to use)
(* Suck/puff used as a single switch input)

Evaluation of tasks

Due to the differences in background, ability and expectations of the various users it is difficult to see any correlation in how useful the different tasks were (Table 13.4). When asked about task areas in a more general sense (Table 13.5) feeding and personal hygiene were both marked poorly by most people, though it was felt that the system might be useful for providing a drink, or for feeding when a carer was not able to be present. Subject L was very enthusiastic about the use of the robot in whatever situation was possible and thought that feeding and personal hygiene were essential tasks for a robot system to be able to carry out.

When asked to mention specific tasks other than those in the list provided, two people mentioned tasks connected with computer use, and office work, one mentioned drinking, another food preparation and one person would have found it valuable for scratching his nose.

	Essential	Useful	No use
Tape	J	GHIKL	
Disc	H	IKL	GJ
Books	L	GHIJK	
Mouthstick	I	H	GJKL
Environmental control	JL	HIK	

Table 13.4 Usefulness of tasks incorporated on the system.

	Essential	Useful	No use
Work	GHK	IL	
Communication	GHK	IL	
Hobbies	GK	HIL	J
Entertainment	GJK	HL	I
Feeding	L	IK	GHJ
Personal hygiene	L		GHIJK

Table 13.5 Usefulness of different application areas

Final response (Table 13.6)

Five people considered that they would use the robot regularly if it were provided to them, three of these being particularly enthusiastic. Two people would consider buying a system while another was sure that she would not be able to afford it.

	Regularly	Occasionally	Never
Would you use such a system if provided?	GHIKL		J

	Yes	No
Would you consider buying such a system?	IKL	H

Table 13.6 Potential usefulness and market of system.

CONCLUSIONS

Encouraging feedback was received from two of the patients at Odstock. It was intended for these trials however that the emphasis should be on home/workplace trials. Two such trials have taken place. In both cases the system has performed well and there have been no problems with the system being used without our presence. The current user is very enthusiastic, and continues to investigate new uses for the system.

Other contacts have been sought through letters to magazines for the disabled and visiting other centres for the disabled. It has been recommended that we should consider the use of the system by cerebral palsy suffers and also by children. These two approaches will present very different problems in the user input aspect.

Results would seem to show that robots can perform a useful function if introduced in an appropriate situation. This will depend on the enthusiasm of the user, his or her needs, and a successful integration into the home or workplace situation. Usefulness must be judged against how tasks could be achieved using alternative methods. This can only be determined through continuing trials of the current system at user's homes or workplaces.

Chapter 14. FUTURE WORK

INTRODUCTION

On the basis of experience with the Wolfson robot we have outlined the design features of a pre-production prototype. This design keeps the main features of the Wolfson System but attempts to overcome the shortcomings of that system.

Additionally alternative mounting arrangements of the arm are suggested which might increase its application, while still using the same basic arm design. It is hoped that these new arrangements might help overcome some of the shortcomings of the workstation approach.

TROLLEY MOUNTED

Mounting the robot in a trolley (Fig 14.1) will enable it to be moved by a carer to various sites within the house. The robot will not need the space of a special desk, but may be fixed to existing tables and work surfaces. At a later date the concept might be extended to a powered or autonomously mobile platform.

WHEELCHAIR MOUNTED

The same basic arm may be used in a wheelchair mounted application (Fig 14.2). The vertical actuator will be mounted on the back of the chair with the arm folding compactly to the rear. This arrangement is to decrease its visual obtrusiveness and to ensure that it does not compromise access through doors. When required for manipulation, an extra link swings the arm round to the side of the user. The arm will have the same reach as a seated person in a wheelchair, though will not be able to reach to the floor.

PRE-PRODUCTION PROTOTYPE

The redesigned features (Fig. 14.3) of the arm for both the existing application and the trolley or wheelchair mounted applications are as follows. Approval has been given for the design, construction and testing of a trial rotary actuator and vertical actuator.

Improved performance

Requirements:

- Reduce friction and motor size for vertical actuator.
- Implement pitch (eg for possible wheelchair application).
- Closer speed control for more effective straight line control.

Solutions:

Rolling bearings for vertical actuator.

Combined pitch and roll using differential gearing at wrist.

Use HCTL 1100 motor control chip. Gives control over speed and position. Requires encoder on back of motor and modified control software.

<u>Easier manufacture and maintenance</u>

Requirements:

Mechanical components to be accessible for servicing.

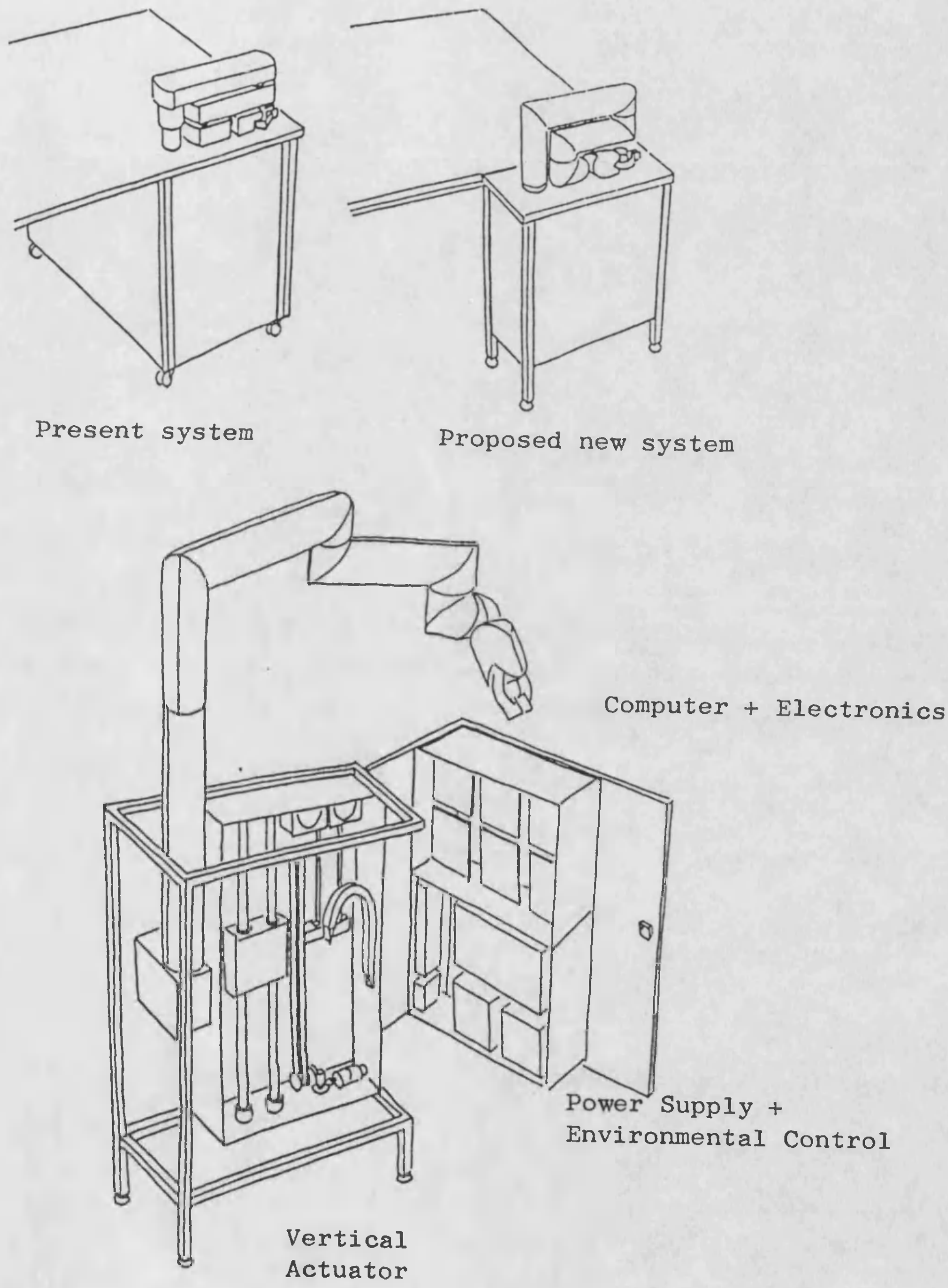
Simplify cabling requirements.

More compact cabinet for mounting on a trolley or a wheelchair.

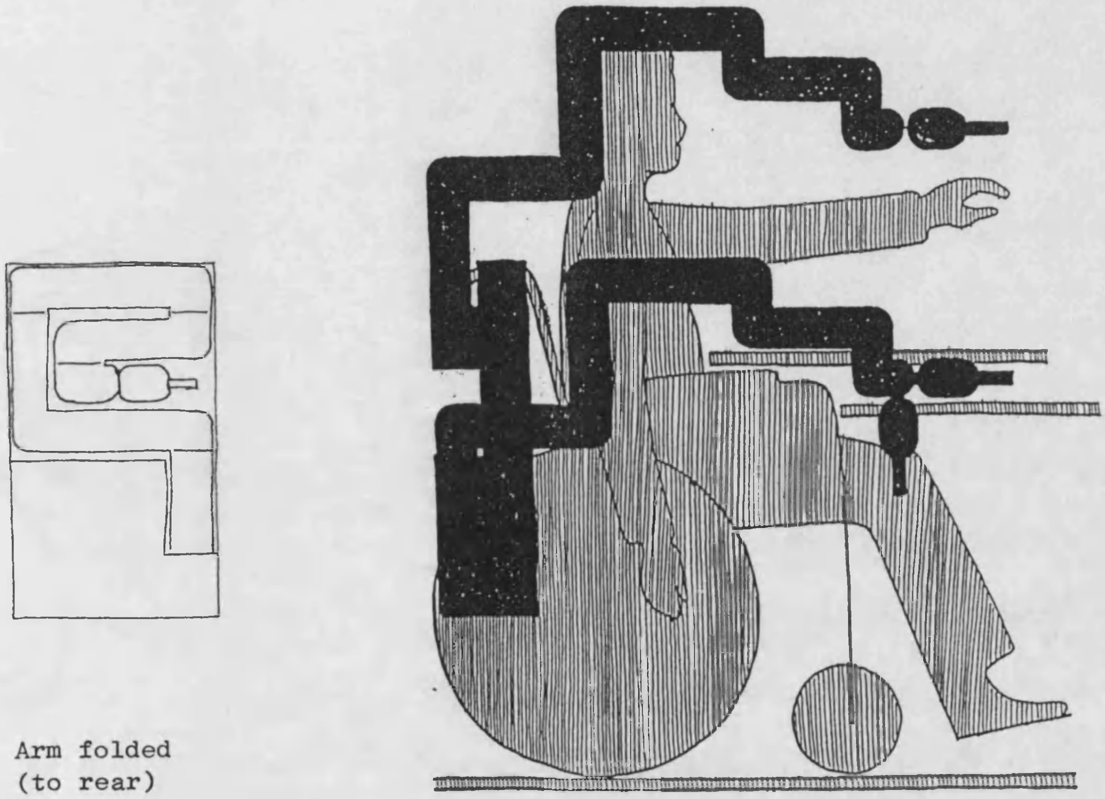
Solution:

Structure to consist of a square section Aluminium extrusion. Motors mounted within structure, but belts mounted outside. Whole assembly covered by a vacuum moulded cosmetic cover. (Users comments called for a more rounded appearance).

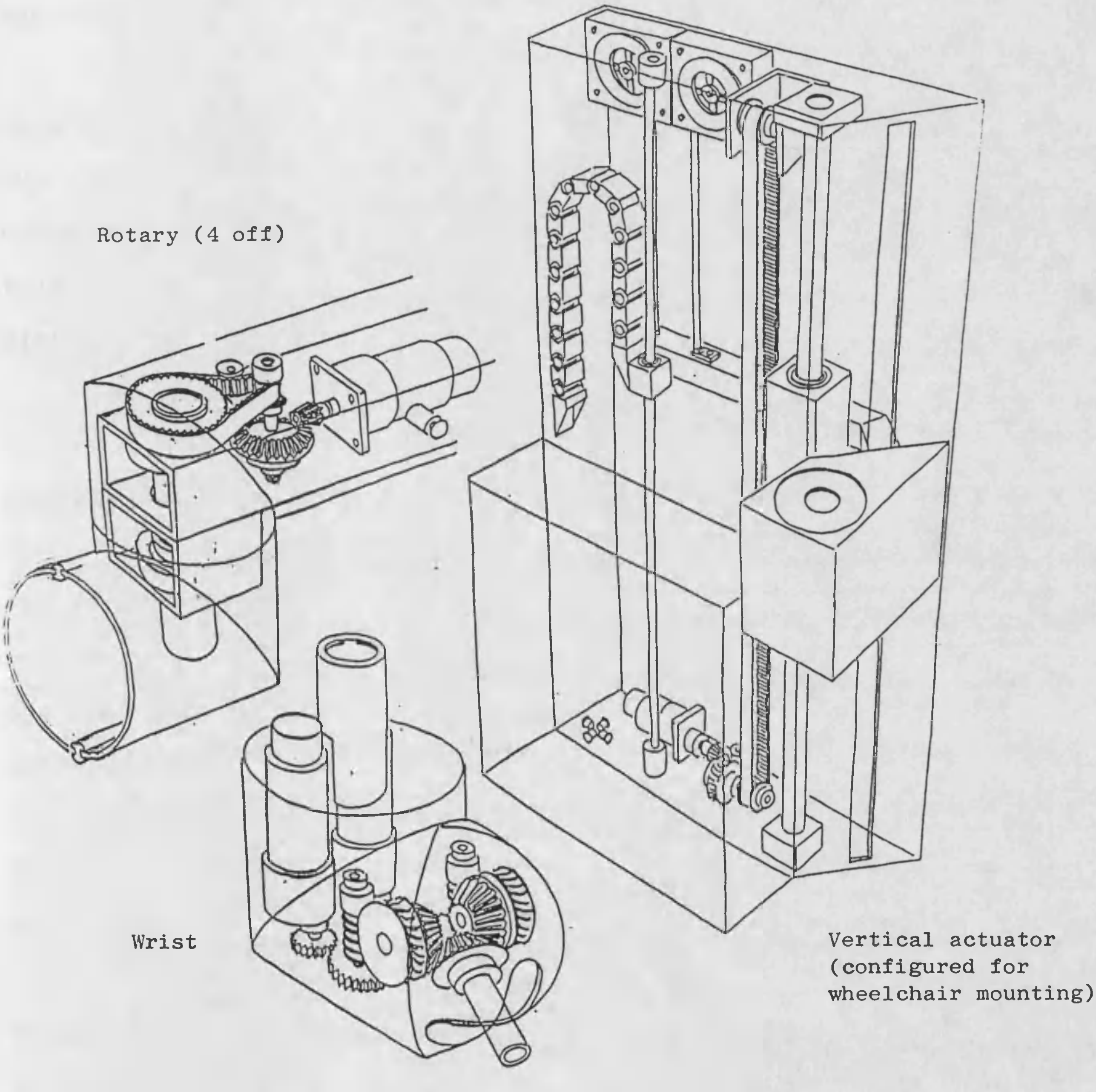
Mount motor control boards within the arm, with an I2C serial link to communicate motor requirements/feedback position.



Mounting of robot system within a movable cabinet. Fig. 14.1



Wheelchair mounting of robot system. Fig. 14.2



Redesigned features of the arm. Fig. 14.3

Chapter 15. DISCUSSION AND CONCLUSIONS

INTRODUCTION

This final chapter evaluates the work at Bath both in terms of the engineering aspects and also experience with users. Other notable projects worldwide are also evaluated. In the light of this experience the whole area of rehabilitation robotics is discussed. Ways forward for the work at Bath are suggested.

EVALUATION OF WORK AT BATH

After three years of the Wolfson project we now have an operative robot system, which is working reliably enough to be placed in a user's home. The robot is compact and has an attractive appearance. Comparisons with the RTX robot are favourable. The user interface is relatively easy to use even for those who can only use a single switch input, and compares favourably with other scanning interfaces.

There are however still shortcomings with the system. The vertical actuator has been a source of several problems, both because of its own performance and due to its corruption of the microcomputer operation. In some positions it sticks with insufficient force to overcome the stiction, yet in other positions it is a concern because of the high force available. Most of the effects of the electrical interference from the vertical actuator have been solved but it still causes spurious turning on of the controlled mains sockets. Position control is not very repeatable, leading to unreliability in the replay of routines. As far as the user interface software is concerned the main problem is that the edit function is extremely difficult to use. The proposed redesign of the system must correct these shortcomings.

User trials have been held at Odstock hospital, at BIME, and in users' homes. The results have been variable. Many of the users have been able to control the system competently, claim that it has great potential, but only for someone in a different situation from their own. A good reponse was obtained from two of the users of the Wolfson system at Odstock. In a hopital environment it was difficult however to determine the real usefulness. The latest ongoing tests have proved most encouraging. The user is keen to investigate all applications of the robot. He sees a robot system as providing valuable independence.

EVALUATION OF PROJECTS WORLDWIDE

Three years ago the Atlas workstation was ready for trials, and we started on the design of the Wolfson manipulator. We now have a working robotic system which has been evaluated by a number of potential users. It is instructive to see what progress has been made by other groups over the same period. The Stanford project has been going for many years but has only now started to produce a useful system. The ADL (Aids for Daily Living) approach has not produced worthwhile results. However the highly structured vocational environment seems to be successful, with at least one system in regular use and others ordered. Each delivered system is individually structured by an engineer for a particular user and situation.

The Vancouver/Neil Squire arm is now commercially available, though very few units have been sold, none directly to disabled users.

The Keele feeding aid has proved highly successful with 40 units supplied, funded by charitable income. Reports are that users find it effective. Some users have improved their posture and mouth control through using the system to such an extent that they can now feed without the aid.

The UMI RTX (and RT100) robot is now widely used in rehabilitation applications. It has become the focus of much research work with many software tools developed for its more effective use. However there are few units in regular use helping the disabled.

The MANUS manipulator is in small batch production for delivery to research centres. We await results from these research centres to know how useful this wheelchair mounted manipulator is in practice.

Very little practical progress has been reported on the application of mobile robot systems. The MoVAR unit developed at Stanford has been discontinued in rehabilitation applications.

DISCUSSION.

The approach of our own work, and of the majority of other groups has been: "Here is a potentially useful area of technology - how can it be applied to aid the disabled". This technology-led approach is always a danger in medical engineering, but we have justified it in this project on the basis of the flexibility of robotics. However, perhaps we are finding that the needs-led approach is always more appropriate. "Disabled people have a particular need - what is the most effective way of meeting it (which may not necessarily be an engineering solution)". It is perhaps misleading to talk about the field of "rehabilitation robotics" with the emphasis on the technology rather than the needs of the disabled. If we look at the successful projects mentioned above we see either examples where the project has been needs-led (as in the case of the Keele feeder) or that the technology has coincided with a need and has been able to meet it effectively (as in the case of the Stanford vocational workstation).

A robotic solution may either meet a specific need of the disabled, or attempt to meet the general need of manipulation, reach and power. It is very difficult to provide general manipulative (etc) ability. This is due both to the technological limitations of our manipulator and gripping device and also the control limitations of the user. It is also doubtful whether one can talk about general manipulation in the context of a workstation system, where the accessible volume is limited by the reach of the manipulator. If we consider the wheelchair mounted arrangement, then it is much more flexible, but even so it has not yet been proved clinically.

If we consider meeting more specific needs we see that "need" may be defined at different levels. For example we have considered the need to insert a floppy disc. However this is only if the person needs to operate a computer, which may be only if he needs employment which may be ultimately because he needs a decent income. The need can therefore be met at different levels. It might be possible to simply provide income in terms of a benefits payment. However there may be advantages of providing employment. If the person is an engineer, then providing access to a computer based CAD system benefits society in terms of the person's skills and benefits the person in terms of social contact, fulfilment and a decent income. However the need to insert a floppy disc is only a means to an end which may in most cases be more efficiently achieved by use of a hard disc drive. (Use of a floppy is only necessary for backup which could alternatively be performed by a tape backup system or loading a new program which, when the need occurs, could be done by a colleague.)

If the robot is seen as meeting a specific need it must be able to do it in the most effective manner. The effectiveness must be measured in terms of the cost of the system, the space it takes up, the execution time and effort required from the user and the reliability of operation. Often, although needs may be identified and accomplished (eg insert tape), a robot may not be the best way of meeting them.

One aspect of meeting needs in the most effective manner concerns the appropriateness of combining different tasks on a single workstation. Looking at our own system the combination of a tape player, a computer and feeding is not an appropriate combination. Similarly the concept of basing the system on a desk may only be appropriate for a vocational system. One needs to identify a situation where there is a high concentration of manipulative tasks which may usefully be performed by a robot, primarily under replay control. Besides vocational, other situations where there are a high concentration of tasks may be a home entertainment centre or the kitchen.

Another aspect of the usefulness of a robot system is the independence which it can give to a disabled person. Simple tasks such as loading a cassette or providing a drink may give a real sense of independence. The psychological benefit of using a robot under one's own control may in some situations outweigh the ease of using a dedicated assistive device. This feeling of independence is difficult to quantify or justify financially, but is vitally important.

CONCLUSIONS

A disabled person with only the most limited movement is able to control a robot manipulator using a single switch operated scanning menu system. In many cases however a more flexible input device, such as a joystick, might be more appropriate. The tests have shown how direct and replay control modes can be effectively integrated.

The use of a relatively cheap robot has been shown to be feasible. Only moderate accuracy of about 1mm has proved quite acceptable. The use of a relatively old fashioned 8 bit microprocessor has not prejudiced the use of the arm to any great extent, though the development process has been restricted by the need to program in assembler.

The system has been able to perform a range of useful tasks and to provide worthwhile independence. The areas of application of robots need to be investigated further.

For a workstation based system the most likely application would be a vocational setting. The precise features would depend on the user. Within such an environment the emphasis should be on efficient and reliable use of preprogrammed routines, though direct control should also be an option.

A more general manipulative application would be as a wheelchair mounted arm. This would be under direct control, but making maximum use of intelligent routines such as gripping.

Mounting a manipulator on a trolley may be a useful approach to extending the usefulness of a robot system without the complexity of a fully mobile system or the restrictions and problems of fitting a manipulator to a wheelchair. The trolley would be wheeled from one site to another by a carer. At each site the system may be able to use preprogrammed routines.

There may be other areas where robot technology can be employed to aid the disabled. Identification of such areas will come from needs being expressed by the disabled, their carers and therapists to engineers who are familiar with the possibilities of robotics.

Appendix 1. DERIVATION OF EQUATIONS FOR THE WOLFSON ROBOT.

DENAVIT-HARTENBERG MATRICES [66]

a.) Draw geometry and number joints, links. (Fig. A1.1)

b.) Values of parameters.

	1	2	3	4	5
theta	0	th2*	th3*	90+th4*	th5*-90
d	d1*	-d2	-d3	0	d5
a	0	a2	a3	0	a5
alpha	0	0	0	90	0

Where * represents variable parameters.

c.) Create transformation matrices.

$$T\ 1\ 0 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d1^* \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$T\ 2\ 1 = \begin{vmatrix} C2 & -S2 & 0 & a2.C2 \\ S2 & C2 & 0 & a2.S2 \\ 0 & 0 & 1 & -d2 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$T\ 3\ 2 = \begin{vmatrix} C3 & -S3 & 0 & a3.C3 \\ S3 & C3 & 0 & a3.S3 \\ 0 & 0 & 1 & -d3 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$T\ 4\ 3 = \begin{vmatrix} -S4 & 0 & C4 & 0 \\ C4 & 0 & S4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$T\ 5\ 4 = \begin{vmatrix} S5 & C5 & 0 & a5.S5 \\ -C5 & S5 & 0 & -a5.C5 \\ 0 & 0 & 1 & d5 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Where:

T n+1 n is the Denavit Hartenberg transformation matrix which maps frame n+1 to frame n.

C2 = Cos(th2), S2 = Sin(th2) etc.

From these matrices can be derived the overall transformation matrices. The problem may be separated into a matrix for the wrist relative to the base, and for the tool relative to the wrist. (nb for this definition "tool" includes roll and yaw).

$$T\ 3\ 0 = \begin{vmatrix} C(2+3) & -S(2+3) & 0 & a3.C(2+3)+a2.C2 \\ S(2+3) & C(2+3) & 0 & a3.S(2+3)+a2.S2 \\ 0 & 0 & 1 & d1^{*}-d2-d3 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Where T 3 0 is the transformation matrix which maps wrist coordinates into the base frame.

$$T\ 5\ 3 = \begin{vmatrix} -S4.S5 & -S4.C5 & C4 & -a5.S4.S5+d5.C4 \\ C4.S5 & C4.C5 & S4 & a5.C4.S5+d5.S4 \\ C5 & -S5 & 0 & -a5.C5 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Where T 5 3 is the transformation matrix which maps tool tip coordinates into the wrist frame.

Multiplying these matrices and taking appropriate parts gives the position and orientation. The upper left 3x3 square matrix gives the orientation while the upper right 1x3 vector gives the position.

Of particular importance is the position of the tool tip relative to the base, with the simplifying assumption that th5=0 (no roll).

$$x = d5.C(2+3+4) + a3.C(2+3) + a2.C2$$

$$y = d5.S(2+3+4) + a3.S(2+3) + a2.S2$$

$$z = d1^* - d2 - d3 - a5$$

SIMPLIFIED MODEL.

For basic straight line motion, only motion in a horizontal plane is allowed, with the wrist kept at a constant orientation. Much simplified equations then give the x and y positions of the wrist. These equations are simply derived from the basic geometry in Figure A1.2. Note that angles phi1, phi2, phi3 have been redefined to operate in a sense away from the parked position.

$$x = a2.\mathrm{Cos}(phi1) - a3.\mathrm{Cos}(phi2-phi1)$$

$$y = a2.\mathrm{Sin}(phi1) - a3.\mathrm{Sin}(phi2-phi1)$$

INVERSE KINEMATIC EQUATIONS FOR SIMPLIFIED MODEL.

This is most easily done by considering the geometry of the problem as shown in Figure A1.3, using the variables h (the distance between shoulder axis and wrist axis) and alpha (the angle which a line between the wrist and shoulder axes makes with the x axis or parked position).

$$h = \sqrt{x^2 + y^2}$$

$$alpha = \tan^{-1} y/x$$

beta and phi2 may be calculated and tabulated as functions of h squared

$$beta = \cos^{-1}\left\{\frac{a_2^2 - a_3^2 + h^2}{2.a_2.h}\right\}$$

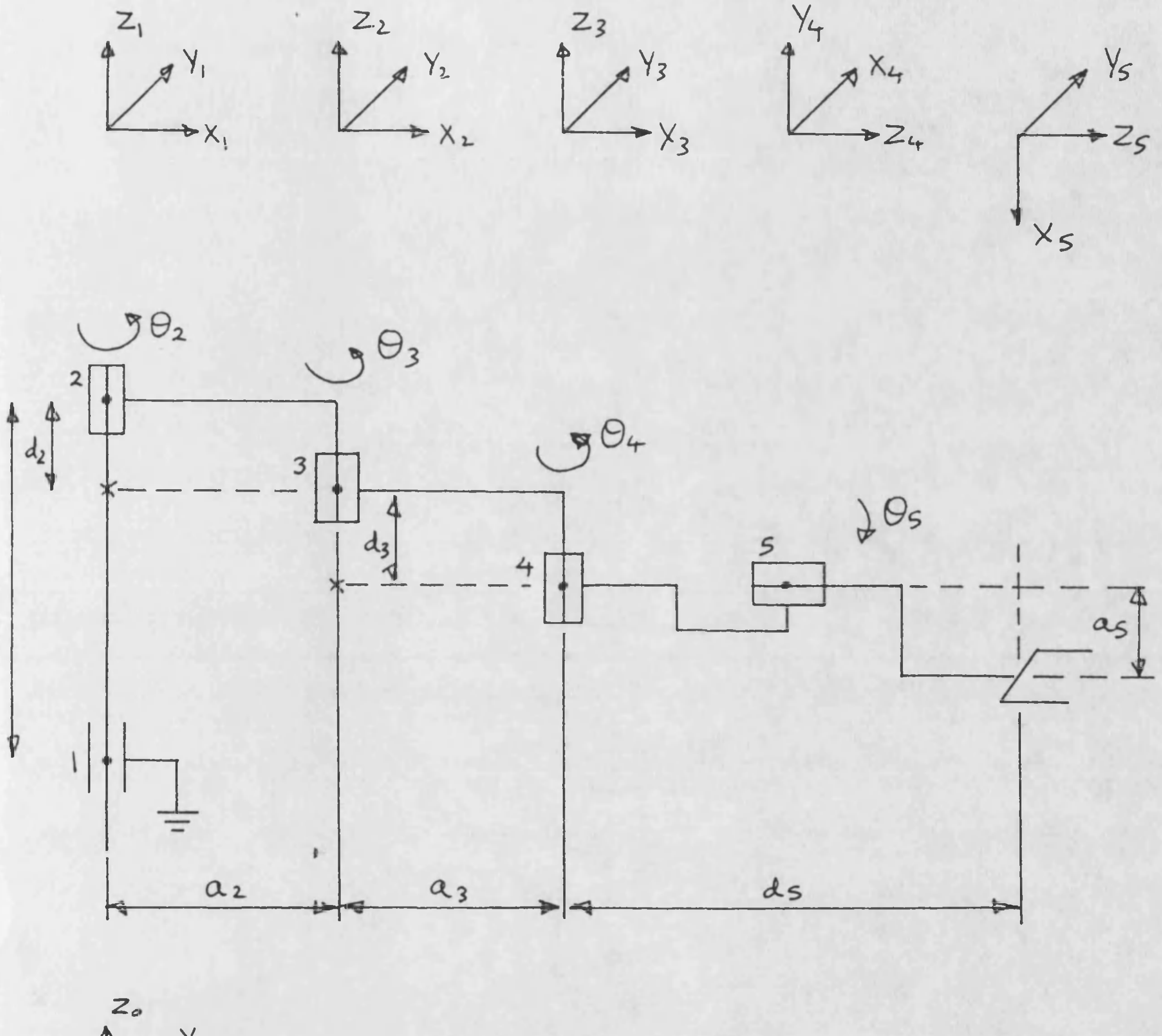
$$phi2 = \cos^{-1}\left\{\frac{a_2^2 + a_3^2 - h^2}{2.a_2.a_3}\right\}$$

Therefore the appropriate angles may be readily calculated

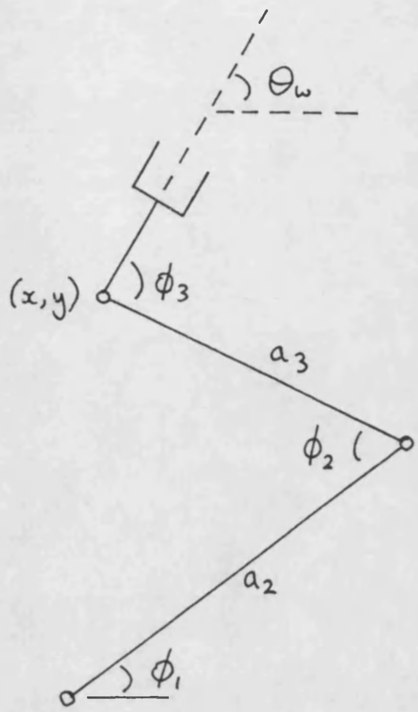
phi1 = alpha - beta

phi2 = as above

phi3 = theta_w + phi2 + phi1



Numbered joints and links for the Wolfson Robot. Fig. A1.1

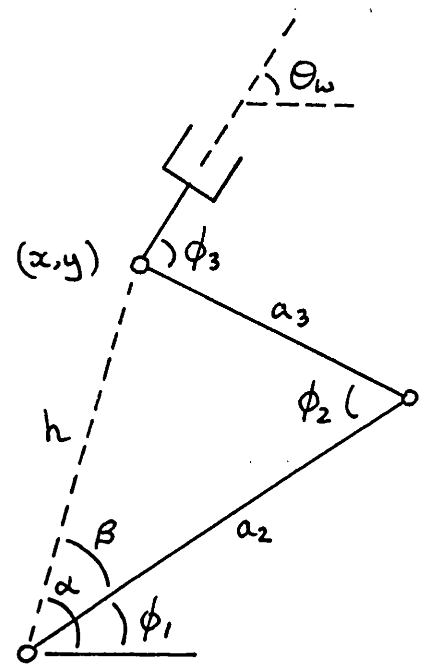


$x = a_2.\mathrm{Cos}(\phi_1) - a_3.\mathrm{Cos}(\phi_2 - \phi_1)$

$y = a_2.\mathrm{Sin}(\phi_1) + a_3.\mathrm{Sin}(\phi_2 - \phi_1)$

$\theta_w = \phi_3 - \phi_2 + \phi_1$

Forward kinematic equations. Fig. A1.2



$$h = \sqrt{x^2 + y^2}$$

$$\alpha = \mathrm{Tan}^{-1}\, y/x$$

$$\beta = \mathrm{Cos}^{-1}\left\{\frac{a_2^2 - a_3^2 + h^2}{2.a_2.h}\right\}$$

$$\phi_2 = \mathrm{Cos}^{-1}\left\{\frac{a_2^2 + a_3^2 - h^2}{2.a_2.a_3}\right\}$$

$$\phi_1 = \alpha - \beta$$

ϕ_2 = as above

$$\phi_3 = \theta_w + \phi_2 - \phi_1$$

Inverse kinematic equations. Fig. A1.3

Appendix 2. SAFETY ASPECTS

A summary of the requirements of robot safety is provided by the science fiction writer Asimov [67] in his three Laws of Robotics.

1) A robot must not harm a human being or, through inaction, allow one to come to harm.
2) A robot must always obey human beings unless that is in conflict with the First Law.
3) A robot must protect itself from harm unless that is in conflict with the First or Second Laws.

Edwards [68], from the Health and Safety Executive suggests a number of guidelines.

* A hazard and risk analysis should be carried out.
* Risks should be decreased by safe mechanical design and limiting speed and power.
* Sensors and current limiting should turn off power in the case of a collision.
* For a specific task, safety devices should be incorporated to deal with the known risks.

Amongst robotics engineers there are two main approaches to robot safety. One approach is to have a system which relies on comprehensive sensors to detect hazard conditions. The other approach is to use hardware design (both mechanical and electronic) which is inherently safe. Since it is impossible to make software 100% reliable, wherever possible software limits should be backed up by mechanical limit stops and electronics with a safe failure state.

The approach used for the Wolfson robot has been the latter. The geometry only uses relatively weak motors in the horizontal plane. Mechanical limits at the actuators restrict motion of the robot near the user. Current limiting is present on all motors. A full hazard analysis has been carried out on the system. The main concern is over the excessive force available from the vertical actuator. Therefore a cut-out switch underneath the wrist will stop the vertical motion on detecting an obstacle beneath the arm.

HAZARD ANALYSIS - FROM USER'S POINT OF VIEW

This first section of the hazard analysis outlines what the hazards might be from the point of view of a user (or other human) and lists safety precautions incorpoated in the system.

1.) Manipulator hits user:

Low powered motors in horizontal plane

Software/mechanical endstops

Manipulator can only just reach user in seated position

Limited maximum speed limits inertia of manipulator

2.) User caught between links of manipulator:

Low powered motors in horizontal plane

Not possible for user in normal seated position

Link offset reduces the scissors effect

3.) Hand (etc) trapped between manipulator and desk top:

Force limited by current limit, friction, counterbalancing

Sensor underneath wrist to cut out on contact

BUT: High force is realisable, therefore a specific warning is issued not to put hands on desk top.

4.) Gripper traps fingers:

Force (2 kgf) insufficient to do harm

5.) Liquid poured by manipulator over user.

High gearing ratio in wrist roll actuator will prevent this under power loss condition.

6.) Weight dropped by manipulator onto user.

Gripper non-backdrivable so power loss will not release grip.

7.) Hazard due to electrical device connected to controlled mains sockets.

Only appropriate devices should be used

(eg don't use non automatic kettle or water heater)

8.) Electrical shock

Whole system is constructed to BS5724, IEC 601

Safety requirements from user:

a) Do not manipulate objects that are both large & hazardous (eg kettle of boiling water)

b) Do not hold sharp or dangerous objects in gripper

c) Keep hands off of desk top

d) Keep children away from the manipulator

HAZARD ANALYSIS - POSSIBLE FAILURE MODES

The hazards listed above may arise from a number of different failure modes of the system. This section lists the possible failure modes and the consequences.

a) Power failure

Mains fuse blow	System dead - motors braked
PSU failure	System dead - motors braked
PCU failure	Unable to turn on/off power supply
Cooling fan failure	Overheating unlikely

b) Electronics fault

Drive transistor blows	Motor at full speed - brake still operative. - software detects condition and operates brake.
Drive op-amp blows	Motor at full speed - brake still operative. - software detects condition and operates brake. I limit trips - brake on
Direction relay fails	Direction one way only
Brake relay fails	Brake on (most likely) or off - speed control still operative

c) Robot computer (EuroBEEB) failure

EuroBEEB computer crashes	User interface computer will detect and reset system. Reset will turn brakes on and mains sockets off.

d) User Interface Fault

User micro crashes	EuroBEEB detects fault when motor is moving, or in the middle of communicating with interface. On reset all motors are braked and mains sockets turned off.
RS423 cable removed	..ditto..
Switch input removed	Switch unable to stop movement
IR communication lost	Switch unable to stop movement
Spurious IR signals	Unpredictable input signals

e) Incorrect operation by the user.

Incorrect operation will be due to:

* Misunderstanding of the control system
* Physical inability to operate switch
* Deliberate action to misuse the system.

The operation of the control system has been designed to be as logical and easy to use as possible. At all stages of the operation, appropriate action of the input will stop the motion. Before all automatic (replay) movements of the arm the system asks the user to confirm. There will always however need to be a compromise between requesting confirmation and operation of the system with as few switch presses as possible.

f) Mechanical failure

Seizure	Motor will stop.
Drive belt breaks) Shaft coupling slip) Gearbox failure)	Will continue due to inertia, slowing due to friction.
Constant tension spring (vertical actuator) breaks.	Stiff bushing will limit motion. Door must be kept locked because of danger from breaking spring. In a production version a safety interlock should be incorporated on the door.

g) Error on controlled mains devices.

If either the EuroBEEB system or the Interface system fails the devices may continue in the state set until the fault is detected. The fault will be detected whenever the two systems communicate. When an error is detected and the system reset, the mains sockets are turned off. However if the devices are being used correctly, and are not faulty, there should be no hazard.

h) Hazard from Electrical shock

The system has been designed and build to BS5724, and is also protected by a RCCB plug.

If the cable becomes detached within the manipulator, there may be the possibility of 24v dc on the casing but this is not critical.

Appendix 3. PUBLICATIONS AND PRESENTATIONS

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